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A survey of permanently-manned lunar base concepts.

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Permanently-Manned Lunar Base Concepts

by

Lorenzo S. Hiponia

June 1989

Thesis Advisor: Dr. Donald v. Z. Wadsworth

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This thesis is a comparative evaluation of various lunar base concepts advocated by leading experts in the field of manned space exploration. Additionally, original design concepts are presented in four appendices. The emphasis is on the impact of mission strategy and objectives on lunar base design concepts. Three candidate mission scenarios involving a lunar base are compared: (1) a scientific research station, (2) a mining and manufacturing facility based on lunar resources, (3) a permanent, autonomous manned base or staging point for space exploration. The lunar base development stages are related to the evolution of the various mission alternatives. In addition, several lunar base design concepts are compared and evaluated in terms of function and construction techniques suitable for the lunar environment. Lunar base power sources are compared in terms of power output, complexity, and feasibility. Particular attention is given to the role of solar and nuclear power and the possible role of superconducting technology. Finally, the transportation infrastructure and logistics required to support an operational Moon base are examined, the primary focus being on mission modes, transportation costs, and supply logistics. This thesis concludes with a feasibility appraisal of a lunar base endeavor and surveys current lunar base study efforts.

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A Survey of Permanently-Manned Lunar Base Concepts

by

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Submitted in partial fulfillment of the
requirements for the degree of

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June 1989

ABSTRACT

This thesis is a comparative evaluation of various lunar base concepts advocated by leading experts in the field of manned space exploration. Additionally, original design concepts are presented in four appendices. The emphasis is on the impact of mission strategy and objectives on lunar base design concepts. Three candidate mission scenarios involving a lunar base are compared: (1) a scientific research station, (2) a mining and manufacturing facility based on lunar resources, (3) a permanent, autonomous manned base or staging point for space exploration. The lunar base development stages are related to the evolution of the various mission alternatives. In addition, several lunar base design concepts are compared and evaluated in terms of function and construction techniques suitable for the lunar environment. Lunar base power sources are compared in terms of power output, complexity, and feasibility. Particular attention is given to the role of solar and nuclear power and the possible role of superconducting technology. Finally, the transportation infrastructure and logistics required to support an operational Moon base are examined, the primary focus being on mission modes, transportation costs, and supply logistics. This thesis concludes with a feasibility appraisal of a lunar base endeavor and surveys current lunar base study efforts.

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First, I would like to express my gratitude to Prof. Donald v. Z. Wadsworth and Prof. Richard D. Wood for their valuable insight, guidance, and assistance in writing this thesis. Prof. Wadsworth contributed the original ideas presented in the appendices. In spite of their busy teaching and research schedules, both advisors dedicated a substantial amount of their own time for my benefit. Secondly, I would like to thank my wife Ria for her patience, understanding, and support during the last six months. Many weekend activities were forfeited as a result of this thesis, yet she never complained.

I. INTRODUCTION

This introductory chapter provides a general description of this thesis and is divided into two segments. The first section presents background information pertaining to lunar base studies. The second section delineates the objectives and limitations of thesis research.

A. BACKGROUND

Although the feat of landing individuals on the Moon signaled the beginning of a new era in space, humans have yet to establish a permanent settlement beyond terrestrial bounds. The exportation of human civilization beyond Earth will mark the next significant milestone in space exploration. Many concepts have been proposed for a permanently manned lunar base. Technically sound descriptions of lunar bases were published as early as 1946; detailed planning for the habitation of the Moon was begun in 1961, shortly after the start of the Apollo program [Ref. 1: pp. 35-36].

Lunar base concepts are in a constant state of evolution, changing as science and technology advance. For example, initial lunar settlement schemes were based on the Saturn V rocket or derivatives of the system [Ref. 1: pp. 35-36]. Figure 1 [Ref. 1: p. 36] illustrates such a concept. Eventually, the Saturn V program was discontinued and new efforts were directed to towards the Space Shuttle. When the Space Shuttle became operational, lunar base elements and components accordingly resembled cargo bay modules [Ref. 2: pp. 1-2]. In the future, the Space Station *Freedom* will be the major source of influence in lunar base design. The prospects of implementing current technology to support

human habitation in low Earth orbit will demonstrate the technology and capability necessary to continually sustain life beyond terrestrial confines. The use of modified Space Station modules on the Moon will increase the feasibility of establishing a lunar base since the utilization of proven technology reduces both costs and risks.

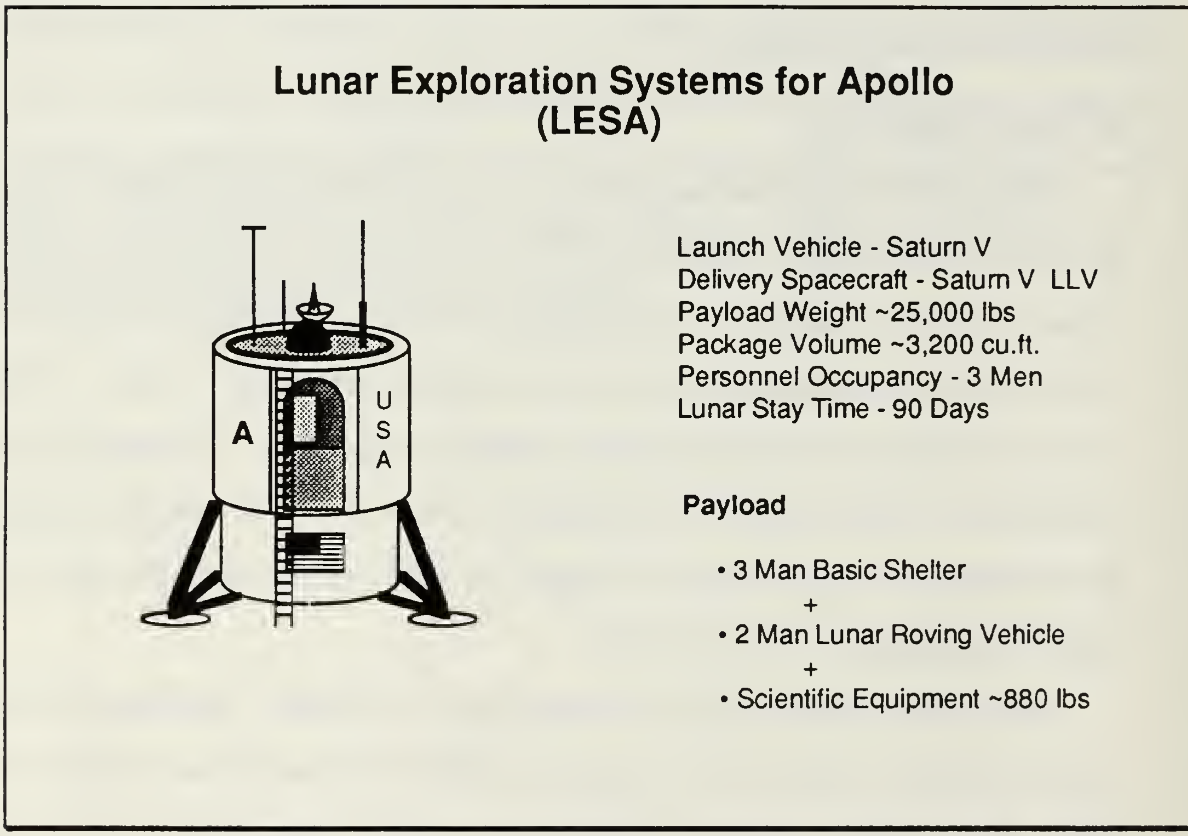


Figure 1.1 An Initial Lunar Settlement Scheme

The objective of this thesis is to evaluate current lunar base concepts advocated by leading experts in the field of lunar studies. The results of published papers, journal articles, National Aeronautics and Space Administration (NASA) reports, and various conference proceedings are the primary source of data. The major focus of discussion will be directed towards

mission strategy and objectives. The specific objectives and limitations of research are defined in the next section.

B. OBJECTIVES AND LIMITATIONS

Prior to the consideration of mission strategy, appropriate background information must be discussed. Key topics include the motivation for establishing a manned lunar base, possible objectives for such a base, and the associated cost considerations of a lunar endeavor. An understanding of these various issues provides the critical insight necessary to analyze the individual elements of mission strategy.

A major concern of mission strategy is to define the role of a lunar settlement in the overall space infrastructure. Although there is a potential military and strategic role for the Moon, this aspect of a lunar base is not addressed within this study. Instead, this thesis presents three distinct non-military scenarios for the development of a lunar base. Experts in this field generally agree that the primary mission of a Moon base should include one or more of three options:

- a scientific research station
- a production and manufacturing facility of lunar resources
- a permanent and autonomous manned base for space exploration

Each scenario shares common prerequisites among the three options. However, each alternative also encompasses specific requirements unique to the chosen path of development. This thesis considers the alternate strategies in the context of phased development and evolution of the individual options. In addition, several lunar base design and construction concepts are presented.

Specific base structures suitable for the lunar environment are introduced. Moon-based power considerations are examined and explored. Possible candidates include solar and nuclear power sources and superconductor power transmission technology. Finally, the Earth-Moon transportation infrastructure required to support an operational Moon base is considered. Primary areas of interest are mission modes, transportation costs, and supply logistic implications. As a conclusion, this thesis examines the overall feasibility of establishing a permanently manned base on the Moon considering the alternative lunar strategies proposed. A brief survey of current programs affecting the pursuit of lunar initiatives is presented.

This introductory chapter has presented the motivational background for this thesis. The scope, objectives, and limitations of research have been listed. The major emphasis is directed towards mission strategy and objectives. The next chapter presents background information pertaining to a lunar base program.

II. BACKGROUND INFORMATION

This chapter presents background information with respect to lunar base efforts. Three topics will be discussed. The first topic examines the motivation for establishing a lunar base. The second topic identifies possible objectives of such a base. The final topic discusses cost considerations pertaining to a lunar base endeavor.

A. MOTIVATION FOR A LUNAR BASE

What is the motivation for establishing a manned lunar base? After all, the ability to deliver an individual to the Moon and insure a safe return has unequivocally been demonstrated by the United States and the Apollo program. Extensive experiments were conducted on the surface of the Moon and an abundant inventory of lunar samples returned to Earth. What more can be gained twenty years after Niel Armstrong first set foot on the Moon?

1. Scientific Investigation

Obviously the results from the Apollo experiments and the associated lunar samples answered many questions relating to the geology of the Moon and other aspects of science. However, new questions were generated from the information provided by the Apollo missions. For example, the general question ,till remains: how was the Moon formed? Apollo findings revealed traditional theories were not consistent with the results of the experimental lunar data. In a 1985 report on lunar bases, Lowman [Ref. 1] cites further uncertainties:

- the composition and structure of the highland crust are only approximately known
- the source and nature of basin-forming bodies are unknown

- the question of whether the Moon is internally active still remains unanswered [Ref. 1: p. 41]

For astronomy research, a base on the far side of the Moon would be an optimum location for a lunar observatory. The far side offers shielding from most terrestrial radiation and as a result, it is the most radio silent location accessible for observations [Ref. 1: p. 41]. Furthermore, the slow rotation rate of the Moon results in a very stable platform desired for astronomy applications. Finally, the lack of a lunar atmosphere increases the clarity and horizon of visible observations magnitudes beyond that which is possible on Earth.

2. National Strategic Interests

Although much knowledge would be gained from a lunar base, a 1984 Los Alamos National Laboratory working group report by Duke *et al.* [Ref. 4] implies that scientific discovery and grand exploration schemes, by themselves, will never justify a manned lunar base. The Los Alamos group believes such an endeavor must inherently support national strategic interests in space [Ref. 4: p. 3]. In the past, the American space program was an effective means of instilling national pride and promoting national prestige. A Moon base could serve the same purpose today by establishing the first human habitation on another planetary body. Not only would long term scientific investigations be conducted, but the processing of lunar materials could be pursued. There is much promise in the prospect of mining regolith (lunar soil) to extract oxygen, silicon, and various metals for local consumption [Ref. 3: p. 85]. The ability to process extraterrestrial resources *in situ* could result in a definitive advantage with regards to national strategic space interests. Moreover, the process of building a lunar base would lead to the evolution of a robust space transportation system.

The technology, science, and equipment involved in a lunar transportation system would place the United States in the forefront of space systems and exploration.

3. Stimulus for Technology

The Apollo program was a significant stimulus not only for space systems, but other technologies as well. Advancements originally developed for space travel were adapted for Earth applications. Unquestionably, Apollo gave the United States a commanding, but temporary, lead in space technology. A renewed lunar program will serve the same purpose today. [Ref. 1: p. 42]

As mentioned previously, an extensive and robust space transportation system would be required to support an operational Moon base. The development of a Heavy Lift Vehicle (HLV) and an Orbital Transfer Vehicle (OTV) are essential elements of the transportation scheme. Improvements in current propulsion systems, advancements in material and composite science, and enhancements in Closed Ecological Life Support Systems (CELSS) are just some advancements to be gained. Alternative power sources suitable for the lunar environment will also be developed. These alternatives have a potential role in the improvement of Earth-based power systems. Finally, an operational lunar base could serve as a stepping stone to Mars and other the planets. All of the required technology for a Mars mission is nearly identical to a lunar endeavor. Thus, a Moon base will provide all of the same technological challenges required for a planetary mission, but at a less expensive cost, shorter mission time, and lower risk potential for the overall mission. Figure 2.1 [Ref. 5: p. 465] depicts a contextual map of space developments encompassed within space operations evolution and space transportation evolution. As Koelle *et al.* [Ref. 5] state, Figure 2.1 illustrates that "... individual stepping stones are part of a scenario to

develop the resources of space in due course of the evolution of our civilization."

[Ref. 5: p. 464]

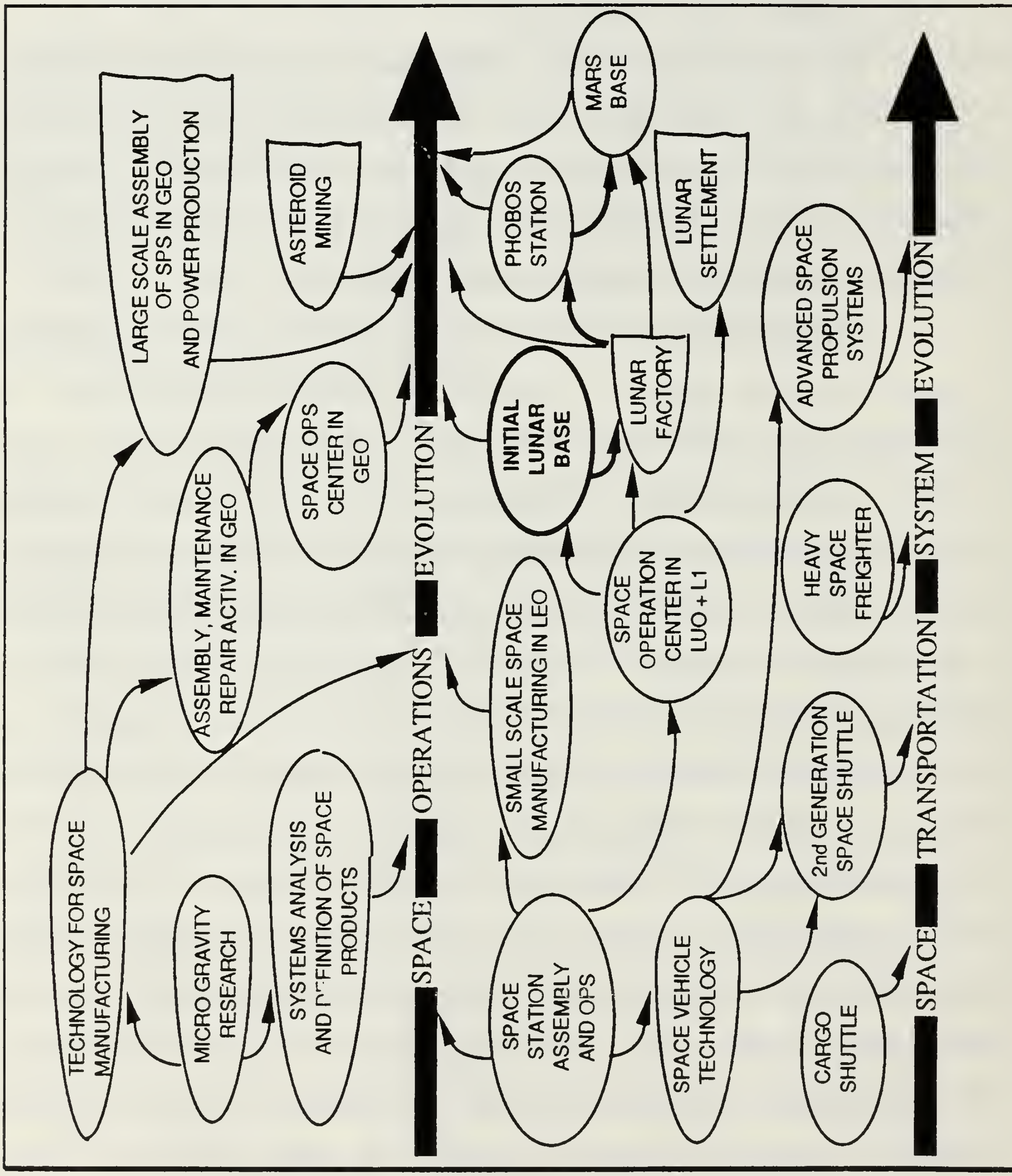


Figure 2.1 Space Developments Map

As a final point on the topic of lunar base motivation, one must consider the views expressed by the National Commission on Space. Created by Congress and appointed by President Ronald Reagan, the commission was tasked to formulate an aggressive civilian space agenda to carry America into the Twenty-first Century. Their 1986 published report [Ref. 3] states the following goal for America to undertake:

> To lead the exploration and development of the space frontier, advancing science, technology, and enterprise, and building institutions and systems that make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars. [Ref. 3: p. 2]

B. OBJECTIVES OF A LUNAR BASE

As shown in the previous section, the Moon is a stepping stone to the vast frontier of space. It will be the first non-terrestrial place humans will inhabit with the aid of local resources. The hostile lunar environment provides a severe challenge to habitation. The permanent presence of people on the Moon will demonstrate the human dominance of a small portion of circumterrestrial space. [Ref. 5: p. 466]

What objectives would a lunar base encompass? First of all, the detailed knowledge and samples of lunar resources gained in the seventies provides a basis for planning the development of extraterrestrial industries. Lunar materials could be used to decrease the cost of space stations. Additionally, lunar industries could supply the shielding and construction materials, propellant, and oxygen necessary to insure continued growth of the lunar base. [Ref. 5: p. 466]

Additional objectives, include long duration manned flights to Mars and mining expeditions to the asteroids. As illustrated previously, basic technologies

would be developed to supply and support such missions. The travel costs for these mission would be reduced by providing refueling and resupply nodes at both ends of an extensive space flight. [Ref. 5: p. 466]

The growth of a lunar operational capability will proceed only with the evolution of a general transportation capability. The entire Earth-Moon logistics system must be thoroughly planned, self-consistent, and mutually supportive [Ref. 4: p. 3]. Table 1 [Ref. 5: p. 467] summarizes the objectives of an international program leading to a permanent lunar base. Four categories are considered: humanistic, political, scientific, and utilitarian objectives.

C. COST CONSIDERATIONS

In a 1986 Los Alamos National Laboratory report, Keaton [Ref. 6] claims establishing a lunar base will require constant funding for a decade and possibly two [Ref. 6: p. 1]. The question is whether such a large space project will be affordable in view of the current economic situation? Even if the answer is yes, there is no way to prove this conclusion. The economic return of a lunar base will not be apparent until twenty years after initial base build-up [Ref. 5: p. 480].

It is therefore important to remember that a lunar base endeavor will be a long term project. The cost of a Moon base is estimated as roughly comparable to the Apollo program. The total amount of expenditures was less than 0.3% of the United States Gross National Product (GNP) from 1962 to 1972. Since Apollo began, the U.S. GNP has more than doubled even after compensating for inflation. The evolutionary nature of establishing a lunar base suggests a life cycle duration twice that of Apollo. A lunar base program, therefore, will cost

less than 0.1% of the current GNP. If necessary, the program can be supported without increasing the historical percentage allocation of NASA. [Ref. 4: p. 21]

TABLE 1. OBJECTIVES OF A PERMANENT LUNAR BASE

(a) Humanistic Objectives	
a.1	Assist in reducing tensions and conflicts on Earth thus contributing to peace on Earth
a.2	Provide opportunity for involvement of a broad spectrum of people in exciting frontier environments
a.3	Enhance the evolution of the human culture
a.4	Establish the first extraterrestrial human settlements as an initial step for expanding human activities in the solar system
a.5	Provide a survival shelter for elements of the human race and its civilization in case of a global catastrophe
(b) Political objectives	
b.1	Demonstrate the potential growth beyond the limits on Earth
b.2	Provide opportunity for international co-operation
b.3	Provide the infrastructure and experience for global enterprises
b.4	Provide a peaceful outlet for national, competitive high technology urges and a useful employment of existing industrial-military capabilities
b.5	Enhance the national prestige of participating nations
(c) Scientific objectives	
c.1	Improve the understanding and control of our own planet
c.2	Improve our knowledge of the Moon and its resources
c.3	Improve our understanding of the solar system beyond the Earth-Moon system
c.4	improve our understanding of the universe beyond our own solar system
c.5	Provide a science laboratory in a unique environment for experiments in physics, chemistry, biology, geology, physiology and sociology which cannot be conducted on Earth
(d) Utilitarian objectives	
d.1	Provide rewarding job opportunities and thus, stimulate the economy on Earth in general
d.2	Stimulate the development of advanced industrial technology on Earth
d.3	Produce marketable space products other than in the aerospace industry for extraterrestrial as well as for terrestrial use
d.4	Contribute to the supply on Earth with renewable solar energy
d.5	Provide an isolated depository to store high-level, long-lived nuclear and other wastes on the far side of the Moon(if legally possible)
d.6	Provide safe and economical space transportation systems including a lunar spaceport and production facilities (mandatory for the exploration and utilization of other celestial bodies of the solar system)
d.7	Provide thrust and focus for continued development of space technology other than space transportation systems

There have been numerous programs funded on Earth whose scale and cost is comparable in magnitude to a lunar base. For example, private enterprise has

invested more than nine billion dollars in the Alaskan Pipeline. The U.S. government has supported the Interstate Highway System with funds exceeding forty billion dollars. The 1,300-mile Grand Canal of China, which was under continual construction for two millennia, represents an even greater investment in terms of monetary value. [Ref.4: p. 21]

Koelle *et al.* [Ref. 5] provide an illustrative cost acquisition analysis shown in Table 2 [Ref. 5: p. 481]. The figures represent the initial investment structure and volume over a period of fifteen years (in 1985 dollars). Although these figures were derived by making a great deal of assumptions, it is an adequate first guess in a lengthy iterative process. These figures serve to illustrate the relative magnitude of dollar costs required for program funding. The specific components of this particular system is representative of other proposed infrastructures:

- a heavy lift launch vehicle (HLV)
- an orbital transfer vehicle (OTV)
- a lunar lander (lunar bus)
- a lunar orbital station
- an Earth orbiting space station.

A detailed discussion of these individual transportation elements will be presented in Chapter VI. Table 2 also includes costs associated with both ground facilities on Earth and lunar base elements on the Moon. Finally, the transportation cost of ferrying cargo and personnel to the Moon's surface is included and summed with the other elements to obtain total cost.

TABLE 2. LUNAR BASE ACQUISITION COSTS

1.	Heavy lift launch vehicle (if charge fully to this program)	15.0×10^9	(1985 $)
2.	Interobital ferry vehicle	6.0×10^9	
3.	Lunar bus	3.0×10^9	
4.	Lunar orbit station	3.0×10^9	
5.	Extension of Earth orbit facilities	3.0×10^9	
6.	Ground facilities on Earth	6.0×10^9	
7.	Lunar base elements	15.0×10^9	
8.	Lunar resources development	6.0×10^9	
9.	Transportation cost Earth-Moon	10.0×10^9	
10.	Miscellaneous	8.0×10^9	
Total		75.0×10^9	(1985 $)
Average annual expenditure (15 years)		5.0×10^9	(1985 $)

Duke *et al.* [Ref. 4] assert that manned planetary exploration must take place in light of today's economic and political realities [Ref. 4: p. 4]. The political pressures of funding a lunar base will be enormous. A great deal of Presidential, Congressional, and public support will be required to initiate such a huge financial undertaking. Of all the obstacles present in a lunar base endeavor, including technological and operational uncertainties, the problem of funding remains the most questionable. As a final thought on lunar base costs, consider Keaton [Ref. 6] and his remarks concerning the funding of the U.S. space program:

> The dangers of not making major long-term commitments now are twofold: An unnecessary miserly approach to our nation's space program can be a self fulfilling prophecy, and without a long-range perspective we run the risk of spending the money unwisely by fits and starts. [Ref. 6: p. 5]

This chapter has presented background information concerning efforts to establish a lunar base. The motivation for a lunar base was examined from the perspective of scientific investigation, national strategic interests, and potential technology stimulus. Possible objectives of a Moon base were listed and finally, cost considerations were examined. The next chapter deals with the strategy of implementing a lunar base program. Specific concepts will be discussed as well as alternatives to a manned lunar base.

III. STRATEGY

This chapter consists of seven sections, A through G, describing the strategy involved in implementing a lunar base program. The chapter strives to survey concepts and notions proposed by experts in the various fields relating to lunar base studies. Section A defines the lunar base concept. Section B lists program requirements of a lunar base endeavor. The following segment, Section C, contrasts and compares alternative emphasis areas for a lunar base program. The next topic, phased development, is covered in Section D. This section differentiates four distinct phases of systematic lunar development. Section E defines and specifies the characteristics of a lunar infrastructure. Emphasizing advantages and disadvantages, alternative concepts are proposed in Section F. Finally, Section G lists environmental considerations related to activities associated with a Moon base.

A. LUNAR BASE CONCEPTS

The term "lunar base" can describe a spectrum of concepts ranging from a temporary exploration and research outpost to a fully developed, self-sufficient colony. The evolutionary growth progression of a Moon base can be easily divided into discrete stages of development. The "final" configuration of the base becomes important when cost figures are considered. In view of the current economic situation, limiting acquisition costs should be a major strategic goal to ensure continued mission funding. Consequently, design concepts must utilize and adapt hardware from previous programs. [Ref. 7: p.33]

Another equally influential element of the design concept is the selection of a base site. This decision is guided by programmatic priorities related to the primary purpose of the lunar base. In an introduction to a 1985 Lunar and Planetary Institute book on lunar bases, Mendell [Ref. 7] raises the question of whether or not returning to the Apollo sites will suffice? He notes that the geology and environment of the landing sites are already well known. Thus, the need for precursor survey missions will be eliminated. [Ref. 7: p. 34]

If science is the highest priority of a lunar base, then scientific research will dominate the selection process. For example, consider the choice of developing an astronomical laboratory. This selection would necessitate a decision to locate the base site on the far side of the Moon to minimize interference from man-made radio frequency noise, in the case of radio astronomy. Alternatively, if long-term strategic goals require the development of an extensive lunar surface infrastructure, early exploitation of lunar raw materials is required. The selection of a site rich in lunar resources would be essential. An unmanned polar orbiting satellite will then be necessary to conduct remote sensing survey missions. [Ref. 7: p. 34]

The three previously mentioned lunar scenarios will influence the composition and configuration of the Moon base. The three alternatives have many common elements, especially in the early stages of development. The later phases, however, are critically dependent on technologies, systems, and elements derived during the early phases of lunar evolution. The logistics costs, base complexity, and structure of the space transportation system are all functions of long-term strategy. The final lunar base conception will manifest some combination of the three idealized alternatives. [Ref. 8: p. 1]

B. PROGRAM REQUIREMENTS

A vital process in defining a lunar base program requires the establishment of goals and objectives for the program. After these requirements have been specified, evaluations of technical readiness, costs, and expected benefits can be accomplished [Ref. 9: p.1]. In considering open questions of lunar base objectives, Duke [Ref. 9] describes four general characteristics of a successful program:

- It should enable scientific advances that are unique and which are sufficiently important to merit support from one or more broad scientific disciplines (planetary science, astronomy, life sciences, etc.) in competition with other potential projects in those disciplines.
- It should spur broad technological advance that provides order of magnitude improvements of capability in important areas, such as space power and space transportation.
- It should improve operational capabilities that provide clearly useful advantages to other space endeavors in the areas of orbital operations, space habitation and industrialization.
- There should be a clearly defined programmatic path linking initial steps in the strategy to the longer-range goals, and there should be a continuing return from the strategy in terms of increased capability and decreased operational costs, lest the program become an operational burden. [Ref. 9: p. 1]

The first three objectives can easily be fulfilled by a lunar base and actually serve as motivational factors (discussed previously in Chapter II). The fourth objective, however, will ultimately determine the success of a lunar base initiative. The importance of a establishing a clearly defined, long-range strategy becomes apparent.

C. PURPOSE OF A LUNAR BASE

This section is divided into three segments corresponding to the three possible emphasis areas proposed for a lunar base: scientific research,

exploitation of lunar resources, and establishing a permanent manned presence beyond Earth. Each scenario will be compared and contrasted to the other two scenarios.

1. Scientific Research

This sub-section will first list environmental advantages of utilizing the Moon as a research facility. Then, opportunities in the various fields of lunar studies will be specified. The branches of science to be examined include astronomy, physics and chemistry, planetology, and life sciences.

a. Environmental Advantages

The Moon is a unique research laboratory due to the presence of certain environmental conditions not easily attainable on Earth. Specific examples are:

- low gravity (one-sixth of Earth's)
- high vacuum (10^{-12} torr)
- seismic stability
- low temperature at poles (50-80°K)
- low radio noise on the far side
- low rotation rate (2 week day/night)
- large thermal gradients
- hypervelocity impact by small cosmic particles (micrometeroids) [Ref. 4: p. 5]

A science oriented lunar base will be a straight forward extension of the Space Station architecture. Common elements include habitation requirements, power needs, environmental control, extra-vehicular activity (EVA) capability, and laboratory facilities. There are, however, key differences in lunar base architecture not applicable to the Space Station. For example, there will be a need to provide some form of surface mobility on the Moon. Systems must be

developed to enable extensive movement about the lunar surface. In addition, modifications of space station technology will be required to compensate for the presence of lunar gravity. Moreover, the long cycle of day and night requires special adaptations of power and illumination sources. Table 3 [Ref. 5: p. 468] illustrates a program which could be developed for establishing a base exclusively for science. [Ref. 5: p. 468]

TABLE 3. TYPICAL LUNAR SCIENCE PROGRAM

Lunar global survey	1990's	Polar orbiter	Maps chemistry, topography, for selection of lunar base site
Lunar base camp	2005	Habitation, 100 km mobility, daytime visits, limited infrastructure	Lunar and planetary science, small astronomical observatory, life sciences research
Lunar science outpost	2010-2015	Expanded habitation long range mobility extensive power communications	Extensive labs, advanced astronomical facilities, physics, chemistry, environment studies

Table 4 [Ref. 5: p. 469] defines the necessary elements of an early lunar base laboratory. Once again, site selection would depend on the specific objectives of the program. For example, if the location of the base were at a highland-mare boundary, both early crust and latter volcanic processes could be studied [Ref. 5: p.469].

TABLE 4. INITIAL LUNAR LABORATORY REQUIREMENTS

Habitation module(s) for support of crew of 7
Regenerative life support system
100 kW power
Moon-Earth communications system
Unpressurized roving vehicle, range of 25-50 km
Solar flare storm shelter
Materials laboratory
20 m drill

b. Astronomy

The Moon offers three distinct advantages over ground-based and Earth-orbital observations:

- the far side is permanently shielded from terrestrial radio frequency emissions
- the Moon's surface provides a solid, seismically stable, low gravity, and high vacuum platform for precise interferometric and astrometric observations
- for at least the next few decades, the Moon may offer the only permanent manned bases beyond the Earth's geocorona (normally located beyond the radiation belts)--thus providing a low background radiation environment [Ref. 4: pp. 6-7]

There are two principle classes of observatories that could be developed. The first class of observatory strives to achieve an ultrahigh (microarcsecond) astrometric positic ıal accuracy and angular resolution through the use of interferometric arrays at microwave, infrared, and visible wavelengths. The second class of observatory attempts to achieve greatly improved sensitivity for the detection of faint sources of electromagnetic radiation at all wavelengths, of charged particles, and of exotic radiators (neutrinos and gravitational radiation). [Ref. 4: p. 7]

A lunar base observatory will permit observation of stellar objects at much fainter magnitudes beyond the Earth-orbiting Hubble Space Telescope. The lunar environment allows new observation wavelengths to be explored. In addition, larger antennas with increased sensitivities to the various regimes of the electromagnetic spectrum could be constructed. Table 5 [Ref. 5: p. 469] lists typical instruments required for a lunar astronomical laboratory, while Table 6 [Ref. 4: p. 7] describes specific types of astronomical observatories possible on the Moon. A lunar observatory will require capabilities inherent to a lunar base.

The location of the observatory could be on the far side of the Moon, or at least near the lunar limb where shielding from the Earth is obtainable. The possibility of a polar site must also be considered. [Ref. 5: p. 469]

TABLE 5. LUNAR ASTRONOMICAL INSTRUMENTS

Large cryogenically cooled IR telescope
Long baseline interferometers and arrays (Moon-Moon; Moon-Earth)
Large single dish radio telescope
Very low frequency far side array

c. Physics and Chemistry

The particular environmental factors of interest in terms of physics and chemistry include the high vacuum of the Moon, easy access to direct sunlight and shadow, the absence of a significant planetary magnetic field, and low vibrational movement. Capabilities such as very long paths for charged particle beams, ease of access to very low or very high temperatures, and the plausibility of radiation from cosmic interactions may allow new investigations to be performed. [Ref. 5: p. 469]

Koelle *et al.* [Ref. 5] note among the research areas that could benefit are: "charged particle accelerators; studies of very long half-life isotopic or fundamental particle decays; hypervelocity acceleration/impact stu ies; nuclear fusion; and surface chemistry analysis." [Ref. 5: p. 469] The Moon presents no large scale obstacles to the solar wind because it lacks both a dense atmosphere and a large scale intrinsic magnetic field. The Moon, therefore, acts as an absorbing surface to the charged solar-wind plasma. Within a few meters of the lunar surface, however, the photoelectron sheath interacts

with the solar-wind electric field. This interaction results in a perturbation of the solar-wind. But beyond five to ten meters above the surface, the solar wind is essentially unperturbed by the lunar presence. [Ref. 4: p. 8]

TABLE 6. LUNAR ASTRONOMICAL OBSERVATORIES

Type	Characteristics	Comments
Optical telescope	25-m aperture, UV resolution~1 milliarcsec	Collecting area 100 times that of the space telescope (ST); sensitivity 104 times that of the ST
Optical interferometer	25-km effective aperture, 1-microarcsec resolution	
IR/Submillimeter telescope	25-m aperture, 0.1-arcsec resolution at 10 microns, helium cooled	Collecting area 2,500 times that of the infrared astronomical satellite (IRAS)
IR/Submillimeter interferometer	1,500-to-3,000-km baseline microarcsec resolution at 10 microns	
Very large-aperture EUV/x-ray telescope	Mirror array or coded aperture/imaging detector	Reflecting area 30 times that of the advanced x-ray astronomy facility (AXAF)
Solar observatory	Milliarcsec resolution	
Cosmic ray observatory	Passive and active detectors	
Gamma observatory	Large aperture, good spectral and angular resolution	
Neutrino telescope	Large mass, complex detectors	
Gravity waves	Large interferometric detectors	

In addition to the solar-wind environment, the Moon spends one-fourth of its orbit transversing the tail of the Earth's magnetosphere. Here, the Moon is shielded from the flowing solar-wind plasma and its associated electric and magnetic fields. Instead, the Moon becomes exposed to plasma and fields

associated with the geomagnetic tail [Ref. 4: p. 8]. Figure 3.1 [Ref. 10 p.48] depicts the Earth's magnetosphere and the resulting interaction with the solar-wind.

A large scale lunar surface grid of plasma and field detectors would allow unique studies of the solar wind and the magnetosphere tail not possible from just a single satellite position. Likewise, chemical releases (barium, strontium, etc.) by the surface launched sounding rockets in the upstream solar wind would allow observations of important plasma phenomena, such as ionization processes and solar-wind sweeping effects. [Ref. 4: p. 8]

d. Planetology

As previously mentioned, despite the abundant amount of information gained from Apollo, there still remains many unanswered questions concerning the origin and evolution of the Moon. These gaps in knowledge have broad implications in planetology research. Specifically, insight into the history of the Earth and other planets will be gained by study of the Moon's bulk composition. Questions must be answered concerning the interior structure of the Moon, the existence of a metal core, the nature of lunar rocks, and the presence of volatile elements within the lunar composition. Firm conclusions can only result from detailed *in situ* study. Consequently, extensive research into the origin of the Moon can only be carried out from a manned lunar base. [Ref. 4: pp. 5-6]

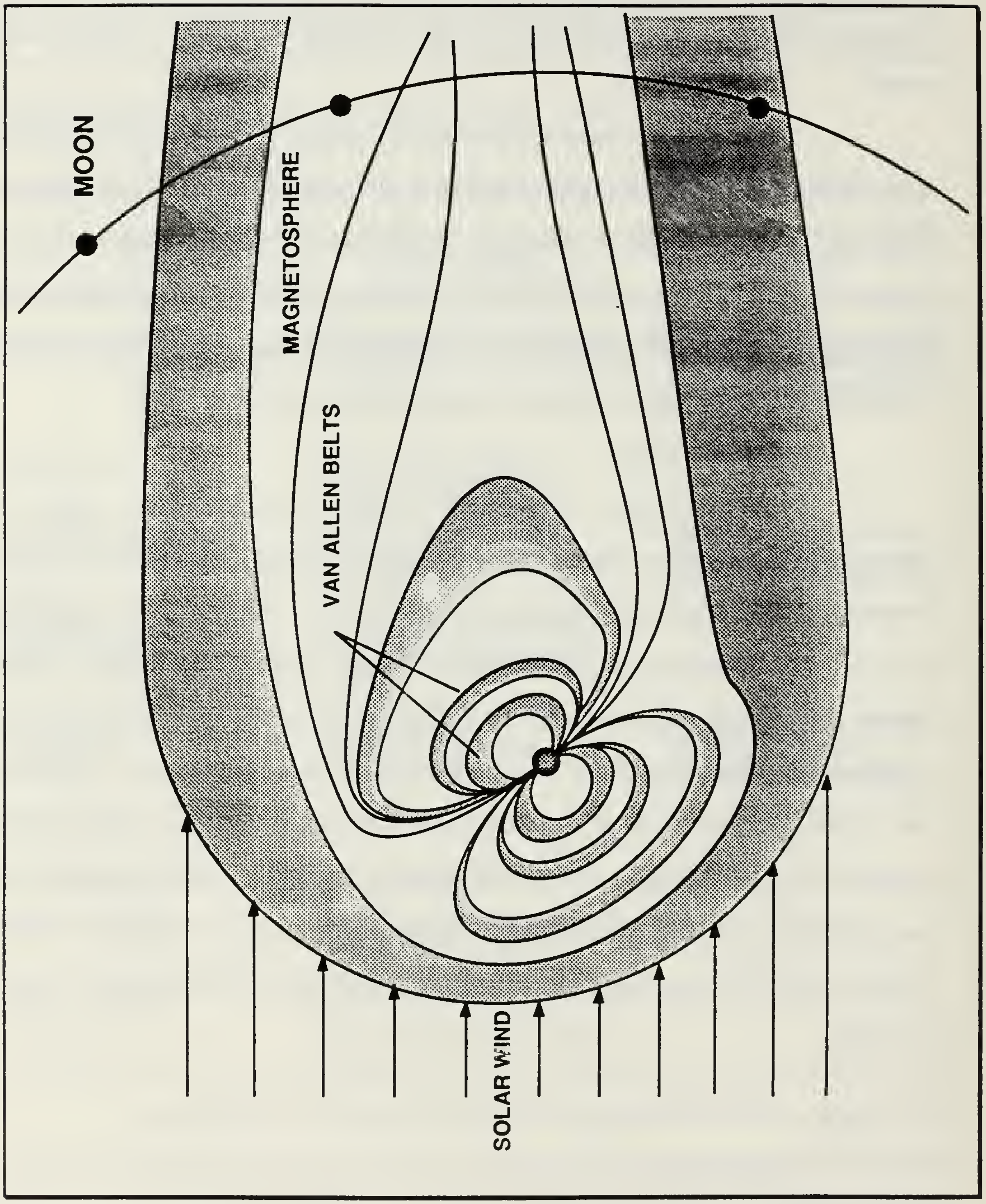


Figure 3.1 The Earth's Magnetosphere

e. *Life Sciences*

Duke *et al.* [Ref. 4] state that there are two general goals of life science studies in space:

- to understand how biological mechanisms (for example, metabolism and growth) function in the space environment
- to develop life-support systems to ensure human safety and mobility in space [Ref. 4: p. 8]

Both goals require extensive study in the unique environment of the Moon. A major concern in the field of life sciences will be the examination of the lunar gravity effects on terrestrial life forms. Additionally, the development of life-support systems utilizing plant life will be pursued. Another major concern will be medical research. A lunar base will provide an environment free of organic material. Thus, experiments requiring ultra-clean conditions could be performed. [Ref. 5: pp. 8-9]

The development of a Closed Ecological Life Support System (CELSS) would be evolutionary and accomplished in stages. Initially, the lunar base would be supported by a space station-like support system. Such a system relies on physical and chemical regeneration of water and air. Furthermore, the resupply of water, air, and food is necessary. When the initial lunar base is established, research will be directed to develop simple biogenerative systems that will supply a portion of the required food, and regenerate air and water. Requirements for an eventual full-scale CELSS mandate the investigation into several technological developments which Duke *et al.* list :

- designing and developing devices to monitor and control systems
- selecting appropriate plant species
- selecting and maintaining appropriate gas pressures and compositions

- selecting appropriate photo-periods and light sources
- selecting appropriate growth media and systems for nutrient delivery
- developing microbial systems to enhance agricultural productivity and stability of general life-support systems
- extracting plant nutrients from lunar materials [Ref. 4: p. 14]

The trend of life-support development will therefore start with physical/chemical systems requiring resupply and gradually evolve into bioregenerative systems [Ref. 4: p. 14].

To summarize the scientific options of a lunar base, Table 7 [Ref. 5: p. 470] presents a list possible lunar research fields. This table provides scientific activities requiring manpower, electrical and thermal power, and miscellaneous equipment and facilities. Obviously, not every activity listed can be performed. In fact, less activity will be possible at the beginning of any lunar science program. Therefore, it is necessary to develop a strategy which prioritizes resources as a function of time.

2. Exploitation of Lunar Resources

There will be a progression of capabilities required in the use of lunar resources. Initially, raw lunar soil will be employed as shielding against radiation. The ability to produce propellant for mass-driver engines in space will be followed by the production of oxygen for rocket propellant. Simultaneously, concrete production capabilities will evolve. [Ref. 3: p. 85]

Concrete production requires the combination of cement and aggregates. Cement is acquired by high-temperature processing of lunar rocks. The required aggregates could be obtained by the physical processing of lunar rocks and soils. Lunar ilmenite would be heated with terrestrial hydrogen to form water. If frozen water is found at the poles, the need for exported water will be

eliminated. Residual iron is a by-product of the ilmenite reduction reaction and could be processed into fibers, wire, and bars for reinforcement. The required casting and curing chambers can be developed from empty fuel tanks left by previous missions. [Ref. 3: p. 85]

TABLE 7. LUNAR RESEARCH FIELDS

1. Global photographic, geochemical and geophysical mapping of the Moon by a polar orbiter
2. Geological traverses across the Imbrium basin region, the younger basins, investigations of lunar highlands and the poles
3. Search for ore mineral occurrences
4. Passive data collection, search for selenologic/geologic activity
5. Astronomic interferometry
6. Radio astronomy
7. Neutrino astronomy
8. Plasma and field observatory
9. Optical astronomy
10. High-energy astrophysical observation
11. Particle physics
12. Sociology/psychology studies and experiments
13. Health and medicine, human functions and performance
14. Exobiology experiments
15. Material science
17. Applied technology
18. Pilot production facilities and processes

From the Apollo missions, it is known that lunar soil is composed of 40% oxygen, 20% silicon, and ~14% metals. Additionally, iron was found to be abundant at every Apollo site. The fine powder was deposited by meteorite bombardment spanning an interval over millions of years. There is a possibility that such fine powder could be gathered by magnetic separation from the lunar regolith. In addition, raw lunar glasses can be used for composites in structures and silicon can be employed in solar cell manufacture. [Ref. 3: pp. 85-86]

a. Use of Raw Materials

There are inexhaustible amounts of aluminum, iron, silicon, titanium, magnesium, and oxygen located on the Moon. Furthermore, the possibility of the existence of hydrogen has not been ruled out by researchers in this field. Lunar material could be electromagnetically launched from the surface at a cost effective rate. The launch energy per unit mass depends on the square of the escape velocity. Therefore, the same mass launched from the Moon would require 22 times more energy than when launched from the surface of the Earth. As such, there is much interest in the use of lunar raw materials for construction or shielding structures in low Earth orbit (LEO). [Ref. 1: pp. 42-43]

Mining, processing, and manufacturing activities are required to bring a raw material to the point where it can be fully utilized. The development of materials processing technologies is vital during the initial stages of development. The eventual goal is to use ordinary and comparatively low-value materials to produce high-value finished products. Manufacturing activities require the development of technology in parallel with advances in material processing efforts. Roberts [Ref. 8] distinguishes material processing by two categories:

- development of technology and demonstration of techniques for producing various types of materials
- demonstration and application of manufacturing techniques and machinery [Ref. 8: p.4]

b. Industrialization

The ability to provide useful products from lunar material will critically affect the capabilities and particularly the growth rate of a lunar base.

Simultaneously, such activities can support other endeavors in space. For example, the possibility of using lunar liquid oxygen for rocket propellant has already been mentioned, as well as the use of lunar soil for shielding. Likewise, the production of ceramic and metal products for space structures can be initiated. The first lunar base will demonstrate industrial capabilities after the initial phase by operating small pilot factories to provide various materials for use on the Moon and Earth orbit. [Ref. 4: p. 10]

Factories for the production of one or two products could be established early in the life cycle of a Moon base. Afterwards, a large effort will be necessary to focus on research, exploration, and operational experience under lunar conditions. Especially important will be the on-site testing of equipment and the success of using indigenous materials. The Moon has ample supplies of various chemical elements already mentioned. Conspicuously absent, except for trace elements, are carbon, hydrogen, and nitrogen. In addition, surface water is absent unless frozen deposits are present near the lunar poles at perhaps a depth of 100 to 200 m (see Appendix D). The lunar soil contains useable amounts of iron-nickle alloy derived from meteorite impacts throughout the Moon's history. Lunar rock or soil can be melted to make glass as fibers, slabs, tubes, and rods. Sintering can yield lunar bricks and ceramic products. Iron metal can be melted and cast or converted into shaped forms through the utilization of powder metallurgy. Possible uses include habitat construction, electrica. power transmission, and shielding materials. Iron, aluminum, titanium, silicon, and oxygen can be liberated from lunar materials through chemical and electrochemical conversion techniques. Silicon can be employed in photovoltaic applications or used to "stretch" the effectiveness of imported hydrogen by

producing silane, SiH_4, a combustible fuel. Silicon and titanium can also be alloyed with iron to make steel. Finally, oxygen has the potential to be an early economical product from an initial lunar base concentrating on production. The specific procedures in propellant manufacturing will be introduced in a later section of this thesis. [Ref. 4: pp. 10-11]

(1) Site Selection for an Industrial Base. Duke *et al.* [Ref. 4] advocate that the most straightforward location for an industrial site is one of the Apollo landing sites. The reason is due to the familiarity of the location site. If the processing facility requires ilmenite concentrates, a soil rich in titanium at a location near basalt would be desirable (Apollo 11 or 17). If feldspar were most needed, a highland site would be preferred (Apollo 16 or 17). Furthermore, the discovery of ice at polar regions could greatly influence the eventual choice of industrial processes and products, not to mention the ultimate location of the base itself. However, the potential value of lunar polar ice is greatly offset by the lack of information. A later section of this thesis will explore the advantages and disadvantages of a polar base. [Ref. 4: p. 11]

c. Market for Lunar Resources

Most lunar material will not merit transportation to the Earth. A possible exception is helium-3, an isotope of helium present in small quantities on the Moon but totally absent on Earth. This isotope has potential for applications in terrestrial fusion reactors. The energy recovered from helium-3 is so great, it may be possible to recover the energy required for extraction and transportation to the Earth by a factor exceeding 200. Note, however, fusion technology is still not developed to the stage where He_3 can be confidently called a lunar resource. [Ref. 5: p. 471]

For space applications, the manufacture of lunar materials on the Moon will be in direct competition with various materials transported from the Earth. However, Koelle *et al.* [Ref. 5] propose that lunar material be utilized for base operations support. Extraction units could be used to replenish expended compounds (O_2, H_2, O, N_2). Rapid expansion of the base would result from the use of metals, sintered products, glasses, ceramics, and lunar-derived concrete. [Ref. 5: p. 471]

d. *Architecture of Lunar Production*

The initial lunar base will rely on local production to achieve objectives in a cost effective manner. Local production will also provide reasonable prospects of growth towards a more permanent lunar settlement. Koelle *et al.* provide three classes of manufacturing or material processing on the lunar surface:

- activities to support the lunar base and its growth
- activities to support other space operations
- activities to support the terrestrial economy [Ref. 5: p. 470]

The first two classes are based on decisions made on the basis of cost to benefit ratios. The third class is long-term in nature, and eventually could be the justification of establishing a lunar base. It is important, however, to consider the evolutionary nature of the production process. From the lunar manufacturing point of view, important considerations include the mass of equipment, man-hours per year expended, personnel safety requirements, probability of success or risk, the impact on the lunar environment, and the scientific or utilitarian value to be gained. [Ref. 5: p. 470]

Table 8 [Ref. 5: p. 472] illustrates the structure and elements of a typical lunar manufacturing program. General tasks and objectives are identified, a timetable is defined, required facilities are specified, and the purpose of each objective is stated. Koelle *et al.* [Ref. 5] propose the basic structure for the first architecture of lunar production in Table 9 [Ref. 5: p. 472].

An initial list of detailed functions required to be accomplished in a fairly advanced lunar base with considerable production capacity is presented in Table 10 [Ref. 5: p. 472]. To carry out these functions, a lunar factory would require the subsystems listed in Table 11 [Ref. 5: p. 473].

TABLE 8. LUNAR MANUFACTURING PROGRAM

Adapt available technology	1980's-1990's	Earth laboratories	Evaluate available technologies
Lunar global survey	1990's	Lunar orbiter	Establish resource potential, select base location
Automated pilot plants	2000-2005	Automated, self-contained landers	Site inspections, 2-3 processes
Human tended small plants	2005-2015	Small package plants; habitation; power	Sortie missions for maintenance
Production plants	Beyond 2015	Full production plants, habitation extensive power	Delivery of product full time maintenance crew

TABLE 9. ARCHITECTURE OF LUNAR PRODUCTION

(I) The primary organizational dimensions are:

(1) Product groups and markets
(2) Functions to be performed
(3) Subsystems and elements required
(4) Locations of activities, facilities and equipment

(II) Locations:

(1) Lunar base camp
(2) Outposts at some distance from the base camp
(3) Lunar orbit
(4) Neutral gravity point between Earth and Moon (L1 libration point)

(III) Product groups:

(1) Air, nutrition, food, water
(2) Propellants
(3) Building materials
(4) Metal products
(5) Non-metal products
(6) Electric and thermal power
(7) Information
(8) Services

TABLE 10. FUNCTIONS OF EXTRATERRESTRIAL PRODUCTION

1. Production of raw materials
    - 1.1 Mining minerals
    - 1.2 Beneficiation of minerals
    - 1.3 Production of raw materials/feedstock
    - 1.4 Production of propellants
    - 1.5 Production of metal products (ingots, sheets, plates, wires, cables)
    - 1.6 Production of non-metallic raw products (fibers, crystals, solar cells)
2. Production / manufacturing of end-products
    - 2.1 Production of structural components and elements (bricks, pipes, panels, mats, brackets, beams, radiators)
    - 2.2 Production of foodstuffs (vegetables, meats, water, air...)
    - 2.3 Production of other products for own use (solar panels, filters, tools...)
    - 2.4 Production of other products for export (energy, helium-3, pharmaceuticals)
    - 2.5 Assembly operations using produced and imported parts and components
    - 2.6 Services produced for export (maintenance and repair of space vehicles, tourism... support of external research activities, rent of laboratories)
3. Direct production support operations
    - 3.1 Supervision and control (of manufacturing processes, facilities and equipment including infrastructure)
    - 3.2 Maintenance and repair of facilities and equipment
    - 3.3 Extension of facilities
    - 3.4 Collecting and recycling (of trash and scrap)
    - 3.5 Storage operations
4. Indirect production support activities
    - 4.1 Local transportation (within extraterrestrial complex)
    - 4.2 Power conversion, storage and distribution
    - 4.3 Habitation (life support, housing, recreation, health services...)
    - 4.4 On site training of personnel
    - 4.5 On site research activities in support of own needs (exploration , observation, experimentation)
    - 4.6 On site administrative services personnel management, financing, planning, legal aspects, public relations...)
    - 4.7 Logistics and space transportation

TABLE 11. LUNAR BASE SUBSYSTEMS

Production facilities and equipment		
(A)	Mining facilities and equipment	
		Earth movers, beneficiation equipments, drills
(B)	Mechanical processing shops	
		furnaces, mills presses, numerically controlled machine tools
(C)	Chemical processing facilities and equipment	
		for gases, liquids and solids
(D)	Electrical/electronic shops	
		circuitry, solar cells
(E)	Biological production facilities	
		food, flowers, animal farms
(F)	Assembly facilities and equipment	
		tools, jigs, shops
(G)	Transportation facilities	
		space and ground transportation systems and facilties
(H)	Power infrastructure	
		conversion, storage and distribution facilities
Infrastructure facilities and equipment		
(I)	Maintenance and repair facilities	
		fixed and movable workshops, tools and equipment
(J)	Research laboratories and facilities	
		contract facilities, product development, research supporting self-sufficiency
(K)	Habitats	
		living quarters, recreation facilities, space suits, hospital training facilities
(L)	Storage facilities	
		propellants, import products, export products, spares, trash
(M)	Control facilities	
		communications, data storage, data processing, operational control equipment, software, administrative facilities

e. Production Facilities and Equipment

The first mining and manufacturing facilities for lunar raw materials will be the key elements of an industrially oriented lunar base. The earliest of these facilities should be designed to operate with a high degree of reliability and automation. Nevertheless, there will be some form of maintenance required to be accomplished by assigned personnel. Therefore, the modules should be also capable of repair, adjustment, and modification by base personnel should the need ever arise. Equipment for modifying the site and preparing the habitat is essential. Two front-end loaders could be used to carve trenches for cut-and-cover placement of habitat modules. In addition, such equipment could provide rocks and soil feedstocks and remove excavated regolith. It is important that perso nel at the lunar base be able to operate vital equipment effortlessly. They should have adequate freedom of movement in order to facilitate the accomplishment of tasks. Ample time should be given for repairs so that personnel can develop variations on operating techniques and thus increase the efficiency of their work. Needless to say, the Moon base should have appropriate laboratories, shops, and maintenance bays. A considerable amount of attention must be given to environmental control. Lunar dust has to be kept out of machinery as well as the buildings which people inhabit. [Ref. 5: p. 11]

f. Propellant Manufacturing

The commodity currently envisioned as the most desired in an Earth-Moon space infrastructure is liquid oxygen (LOX) [Ref. 11: p. 60]. Six-sevenths of the propellant mass utilized by cryogenic systems (hydrogen-oxygen) is LOX. Even if the hydrogen component of fuel is required to be transported

from Earth, lunar produced oxygen would still benefit the space transportation system. Figure 3.2 [Ref. 11: p. 61] illustrates that the mass payback ratio for lunar LOX delivered to low Earth orbit (LEO) is sensitive to the design characteristics of the orbital transfer vehicle (OTV) utilized in the capacity of a space freighter. Key parameters include the fractional mass of the OTV aerobrake and the oxydizer to fuel ratio. An aerobrake is an "air brake" used to slow a spacecraft transiting the upper layers of the atmosphere [Ref. 3: p. 196]. Since the drag of the atmosphere effectively reduces the spacecraft's velocity, a considerable amount of propellant is conserved. Manufacture of aerobrakes on the Moon would enhance the overall transportation system performance. [Ref. 11: p. 61]

Figure 3.3 [Ref. 11: p. 62] provides a simple cost-benefit analysis based on the assumption that a lunar oxygen facility has its capital costs amortized solely by "profits" gained by the delivery of LOX to LEO. While lunar oxygen is quite competitive with shuttle delivery in all cases, the introduction of a cost-efficient heavy lift vehicle derived from shuttle technology (SDLV for shuttle derived launch vehicle) reduces the advantage under more conservative cost estimates for lunar operations. If costs of lunar LOX are distributed with other activities, the advantage is restored. [Ref. 11: p. 62]

Minerals required to manufacture oxygen on the Moon are abundantly available. Attractive raw minerals for this purpose include:

- olivine [(Mg,Fe) SiO_4]
- pyroxene [(Ca,Mg,Fe) SiO_3]
- ilmenite ($FeTiO_3$)

Major minerals such as olivine, pyroxene, and plagioclase feldspar [(Ca,Na) Al_2 Si_2 O_3] occur in concentrations approaching 100%. Minor minerals generally exist in concentrations of less than 2%. However, some of these minor minerals do appear in greater concentrations. Specifically, ilmenite can be found in concentrations of up to 20%. [Ref. 12: pp. 169-170]

Apollo samples have confirmed the chemical composition of lunar minerals of interest. For oxygen manufacturing, the focus will be directed towards concentrations of silicon dioxide and iron oxide. The concentration of magnesium oxide will be importanı for the manufacture of lunar silane. Note the high concentrations of these oxides in lunar olivine as illustrated in Table 12 [Ref. 13: p. 170].

(1) Propellant Properties. The use of liquid oxygen in propellant applications is well established. In a 1985 paper discussing lunar-based propulsion systems, Rosenberg [Ref. 13] cites the Space Shuttle Main Engine (SSME) and the Centaur upper stage RL-10 engine as current examples [Ref. 13: p. 173]. Table 13 [Ref. 13: p. 173] is a comparison of values for the physical properties of oxygen, silane, and methane. Silane has a broader liquidus range than methane. This property benefits the propulsion system and rocket engine designer. Another advantage, silane is hypergolic when combined with oxygen. Methane and hydrogen, on the other hand, are not hypergolic with oxygen. Consequently, the propulsion system increases in complexity. Although its

chemical properties have not been adequately defined yet, silane does appear to have the potential of a storable space propellant. [Ref. 13: p. 173]

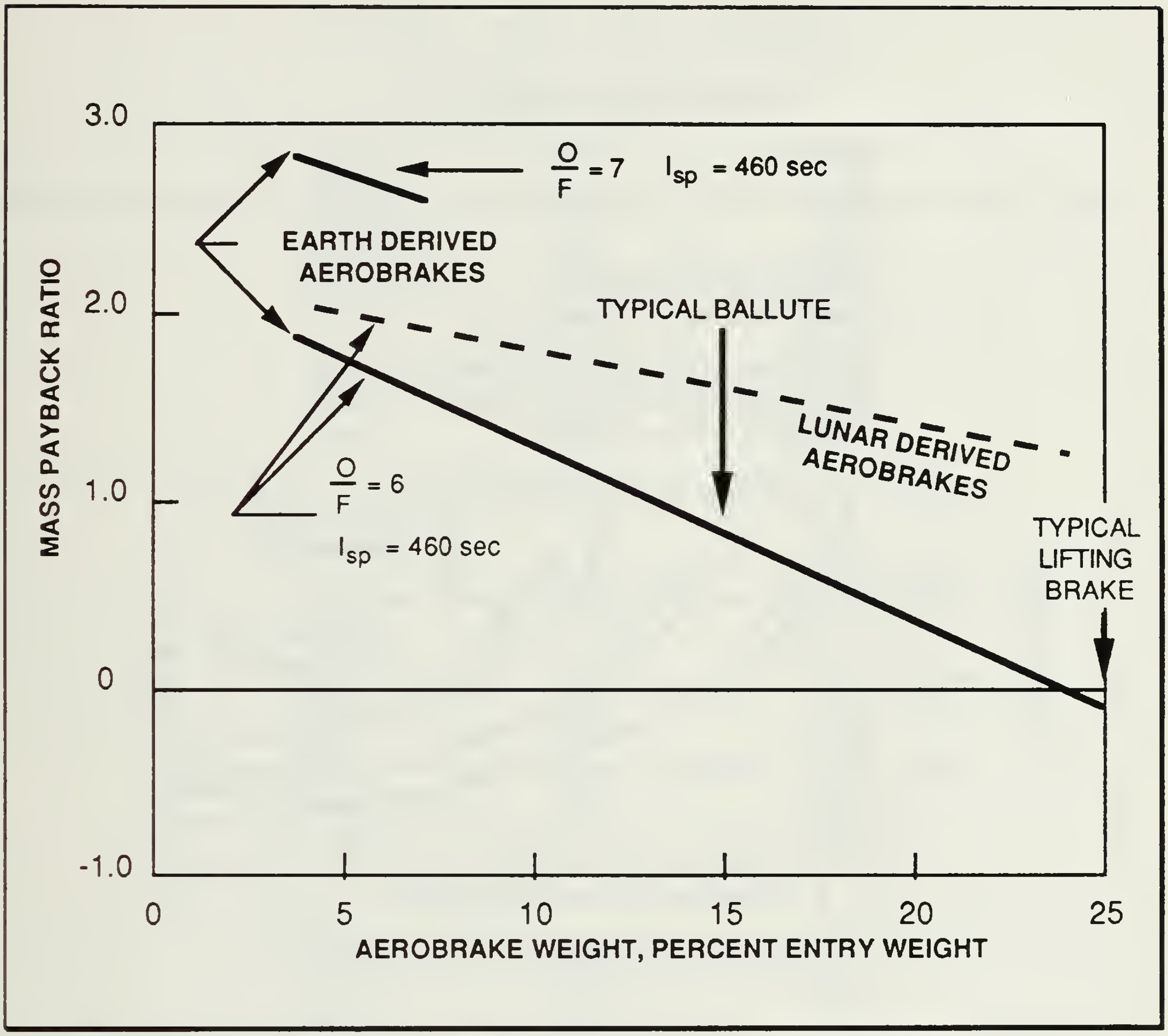


Figure 3.2 Mass Payback Ratio

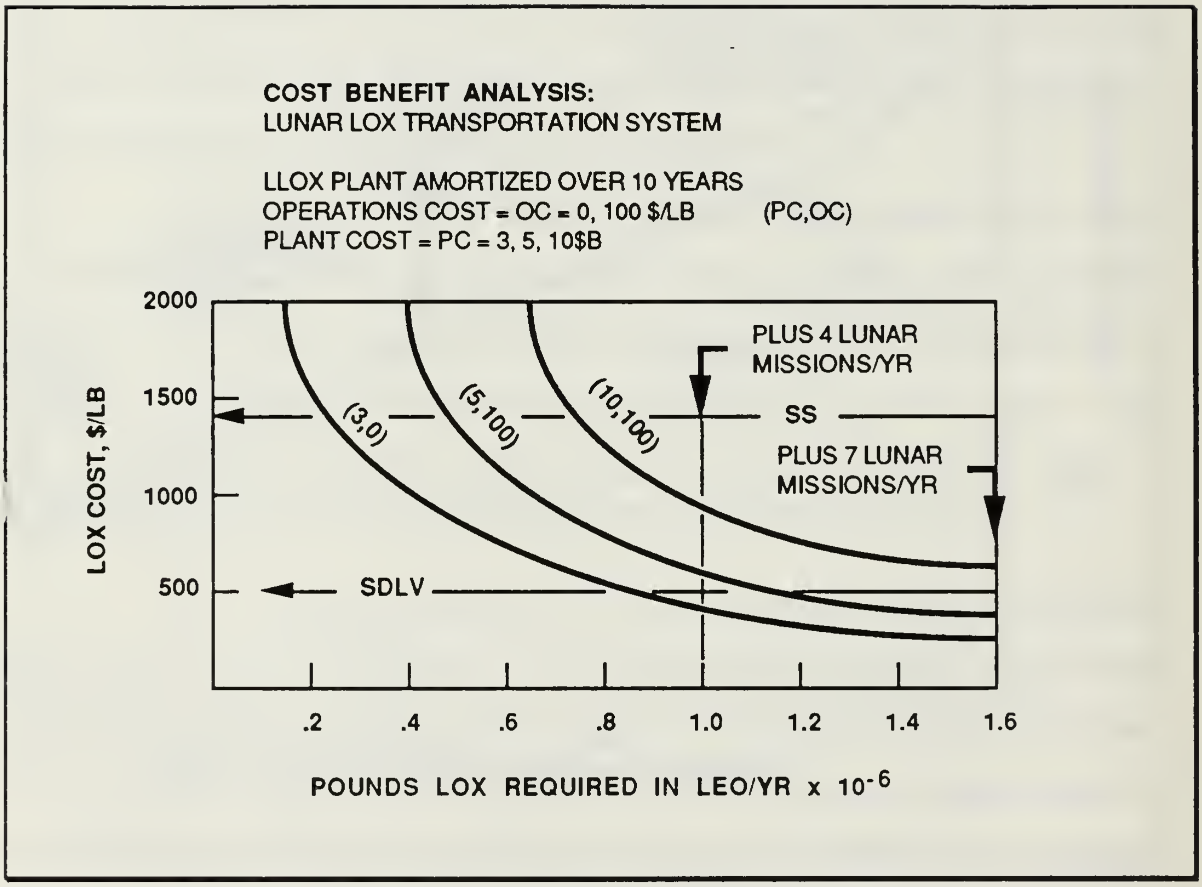


Figure 3.3 Cost Benefit Analysis

TABLE 12. APOLLO SAMPLE ANALYSES

Compound	Mare, wt %	Highland, wt %
	Analysis of Typical Lunar Olivine	
SiO_2	37.36	37.66
TiO_2	0.11	0.09
Cr_2O_3	0.20	0.15
Al_2O_3	< 0.01	0.02
FeO	27.00	26.24
MnO	0.22	0.32
MgO	35.80	35.76
CaO	0.27	0.16
Na_2O	< 0.01	< 0.01
Total	100.97	100.40
	Analysis of Typical Lunar Pyroxines	
SiO_2	47.84	53.53
TiO_2	3.46	0.90
Cr_2O_3	0.80	0.50
Al_2O_3	4.90	0.99
FeO	8.97	15.42
MnO	0.25	0.19
MgO	14.88	26.36
CaO	18.56	2.43
Na_2O	0.07	0.06
Total	99.73	100.39
	Analysis of Typical Lunar Ilmenite	
SiO_2	0.01	0.21
TiO_2	53.58	54.16
Cr_2O_3	1.08	0.44
Al_2O_3	0.07	< 0.01
FeO	44.88	37.38
MnO	0.40	0.46
MgO	2.04	6.56
ZrO	0.08	0.01
V_2O_2	0.01	< 0.01
Na_2O	< 0.01	0.13
Total	102.16	99.37

TABLE 13. PHYSICAL PROPERTIES OF PROPELLANTS

Propellant	Melting Point °F	Melting Point °C	Boiling Point °F	Boiling Point °C	Specific Gravity (liquid)	
Oxygen, O_2	-361.0	-218.4	-297.0	-183.0	1.142	(-297.0°F)
Silane, SiH_4	-301.0	-185.0	-169.4	-111.9	0.680	(-301.0°F)
Methane, CH_4	-296.7	-182.6	-258.3	-161.3	0.460	(-296.7°F)

1. SiH_4 is thermally stable to *ca.* 800°F.
2. O_2/SiH_4 is hypergolic.
3. SiH_4 is a liquid at nbp of O_2

(2) A Lunar-based Propulsion System. Pressure-fed bipropellant engines are attractive because of their relative simplicity. However, several disadvantages must be considered: lower performance values, the requirement for heavier weight tanks, and a tank pressurization system. This combination of factors results in a heavier propulsion system. Ultimately, more weight will be required for propellant and engine mass. [Ref. 13: p. 173]

The penalties associated with an Earth-launched system would have to be reassessed in view of the reduced gravity of the Moon. In a Moon-launched system, the disadvantages of a direct pressure system may be less severe, and a pressure-fed engine operating at a higher chamber pressure may be warranted. Detailed analysis would be required to address these and other uncertainties resulting from the selection a pressure-fed propulsion system. [Ref. 13: p. 174]

Rosenberg [Ref. 13] cites an Eagle Engineering study on the impact of lunar-produced silane upon lunar oxygen production logistics. A primary focus of the research was the transfer of lunar-produced oxygen from

the Moon to low Earth orbit. A comparison was made between the use of a pumped-fed LO_2/LH_2 propulsion system and a pressure-fed $LO_2/LSiH_4$ system. The specific thrust (I_{sp}) of the liquid hydrogen propulsion system was 480 seconds and the mass ratio (MR) was 6.00. For the liquid silane system, the I_{sp} was equal to 345 seconds and the MR was equal to 1.80. Lunar produced silane was used as the fuel in the propulsion system in place of Earth-supplied hydrogen. Rosenberg cites that a small gain of 2.5% in the mass of oxygen transferred was achieved by substitution of silane for Earth-supplied hydrogen. The $LO_2/LSiH_4$ propulsion system only results in a modest benefit despite the advantage of 135 seconds difference in assumed specific impulse values.

However, Eagle Engineering's sensitivity analysis indicates that the use of a 5.0% higher mass ratio and a 1.45% increase in specific impulse for the propulsion system results in a 29% increase in the mass of lunar-produced oxygen delivered to orbit for each ascent. Such improvements can be obtained by the development of a pump-fed $LO_2/LSiH_4$ propulsion system. There is still a considerable amount of research and development required to put such systems in operational commission. However, this developmental stage should be straight forward, since no new technology is required to transition from research to production. [Ref. 13: pp. 174-175]

3. Towards Self-sufficiency

Initially, all activities in space will depend heavily on products obtained from an Earth-launched facilities. As the the amount and complexity of space activity increases, a greater reliance on low gravity, non-terrestrial sources will result [Ref. 13: p. 12]. The rate at which materials become available will inevitably affect cost. Therefore, the rate of growth in space will be dependent

on the development of a proper lunar infrastructure [Ref. 13: p. 12]. Even from the long-term point of view, self-sufficiency in space does not necessarily mean an ability to produce everything independent from Earth. For the reasonable future, it will be easier to make small, sophisticated, and light weight items on Earth for eventual transfer to the Moon [Ref. 13: p. 12]. The requirements for industrialization and ultimately self-sufficiency have previously been presented. True growth capacity requires growth in power and capital equipment, automation and robotics. Logistics costs will be a definite factor. The specific elements of a self-sufficiency scenario will be examined in the following section which deals with the phased evolution concept of a lunar base.

D. PHASED DEVELOPMENT

The process of establishing a lunar base will be evolutionary. It is unrealistic to conceive that such a large project can be completed in one mission. If one considers the logistics alone, the need for phased development, that is, building on the systems previously established, becomes a necessity. Roberts [Ref. 8] gives his own perception of phased evolution in the following description:

> ...the development of the lunar base is subdivided into mutually interactive phases where technologies, systems, and elements developed in earlier phases are prerequisite to the later phases. [Ref. 8: p. 6]

The systemic development of a Moon base can be divided into four distinct phases. Phase I is the is the precursor and preparatory exploration stage. Phase II is the establishment of an initial surface facility limited to research. Phase III is an operational lunar base characterized by the commencement of permanent occupancy. Phase IV is an advanced base, specialized in one of the three scenarios mentioned (science, industry, or self-sufficiency).

1. Preparatory Exploration

Initially, preparatory exploration will encompass unmanned survey missions. Later, manned expeditions will be required to further investigate potential location sites. Finally, an efficient logistical plan must be enacted to support these precursor missions.

a. Survey Missions

The first step in lunar base development will be a detailed global mapping survey of the Moon. This initial phase is required due to the incomplete amount of information known, especially regarding the polar regions. Unmanned satellites will be used for high resolution imagery and remote sensing of chemical variability [Ref. 11: p. 62]. In addition, probe missions will drive penetrators into the lunar surface for on-site analysis and return samples destined for Earth. As mentioned previously, Phase I activities should include research on technology required to exploit lunar resources. Such a process will undoubtedly require a long lead-time to accomplish.

b. Manned Expeditions

Manned exploration during Phase I will consist of actual site selection and reconnaissance. In their 1985 paper, Hoffmann and Niehoff [Ref. 14] have described in detail the necessary composition of such a manned exploration team. They propose a four member team to explore the surface of the Moon for 30 days at a time. This exploratory team will be tasked to search a region 50 kilometers in radius. The site will be a location previously determined by remote sensing data. Logistical requirements include two surface vehicles with a crew compliment of two members. These vehicles will operate in tandem for safety considerations. Each vehicle will consist of a rover and trailer, the

latter consisting of crew quarters and facilities to conduct experiments. The rovers will have the ability to move a considerable amount of lunar soil in order to expose the underground strata composition. A total mass budget of 2400 kilograms is assumed for the instruments which will be used determine the optimal base site. These instruments will focus on local composition, seismic characters, and stratigraphic make-up. Preliminary data analysis will be accomplished on-site, while detailed analysis will be conducted on Earth. These results will ultimately determine the site location of the base. [Ref. 14: pp. 71-72]

c. *Logistics*

The base deployment segment of the mission is expected to last 60-90 days. The two stage process will require twelve shuttle launches and four sorties by an OTV. Initially, the shuttle launches will deliver the necessary equipment and fuel to LEO. Then, two sorties by the OTV will deliver the lunar rovers and trailers to the surface of the Moon. In addition, an unfueled lunar lander/launcher will be placed in low lunar orbit (LLO). The two remaining OTV sorties will be used to deliver and recover crew members. After the mission is completed, all surface equipment will remain on the Moon for use by research personnel. [Ref. 14: p. 72]

By the completion of Phase I, the initial location for the base site will be fairly well defined. Furthermore, planned activities for the Moon base will be understood in some detail. Concurrent with this preliminary development phase should be the development of a space transportation system capable of supporting the Space Station and an orbital transfer vehicle. [Ref. 11: pp. 62-63]

2. Research Outpost

An initial surface facility will be established in this particular phase. In addition, distinct transportation capabilities are required. One possible initial base configuration can be derived based on functional requirements. Finally, a multitude of experiments will be performed. The nature of these experiments depend on the primary thrust of the lunar base.

a. Surface Facility

During Phase II, an initial surface facility would be established. The major emphasis of the facility will be science, materials processing, or lunar surface operations. Depending on which scenario is chosen, the plans diverge from this point on. If the focus were on science and astronomy, activities will include local geographical exploration, the establishment of a small observatory, and the emplacement of automated instruments. However, if production was the major emphasis, then a pilot plant for initial oxygen extraction will be established and the fabrication of aerobrakes from lunar materials will be pursued. Finally, if self-sufficiency was the primary concern, an emphasis would be placed on agricultural experiments utilizing lunar soil. Additionally, more efficient methods of recycling water, oxygen, and carbon dioxide will would be explored. [Ref. 11: p. 63]

b. Transportation Requirements

In order to accomplish Phase II, the space tiansportation system must have the capability of landing and launching from the Moon. Manned capsules up to 10,000 kilograms and payloads up to 20,000 kilograms must be delivered to the lunar surface. Approximately 40,000 kilograms will be required for transport by OTV. [Ref. 11: pp. 63-64]

c. Initial Configuration

Figure 3.4 [Ref. 14: p. 72] illustrates a proposed configuration for an initial lunar base. Each of the three main modules are buried to provide thermal and radiation protection. The rovers have been left by the exploration crew and are utilized to position the modules and cover them with soil. The three modules are connected by an airlock/interface module. Power is supplied from a 100 kW nuclear power source. Table 14 [Ref. 14: p. 73] depicts a possible strategy for deployment and initial operation of the lunar base. [Ref. 14: pp. 72-73]

The strategy illustrated in Table 14 consists of a seven member crew requirement: six scientists and one lunar lander/launcher pilot. The tour of duty will be four months in a staggered rotation. One-half of the crew will be transferred every two months. This arrangement will ensure some continuity of experience available. In addition, two unmanned logistical resupply missions will be flown each year to replace base consumables. An annual requirement of 18 shuttle flights and eight OTV sorties is estimated. [Ref. 14: pp. 72-73]

d. Experiments

An assorted range of experiments can be conducted at this initial base. As can be seen in Figure 3.4, a chemical processing plant has been included in this initial configuration. This facility will enable investigations of lunar raw materials. The extent to which resources can be extracted from the lunar soil will be determined. Likewise, selenology experiments utilizing the rovers and trailers left by the reconnaissance team will be conducted. These trailer facilities can be enhanced with materials transported from Earth. Excursions with these units will place automated sensing equipment well beyond

the base site. Finally, life science experiments in health maintenance and food production will be conducted. As base operational experience is gained, the various experiments can be expanded and enhanced. [Ref. 14: p. 73]

3. Permanent Occupancy

Phase III is the permanent occupancy stage of lunar base development. At this point, the Moon base will be an operational facility. The surface infrastructure will expand to include greater power access, better mobility, and a more diverse research capability [Ref. 11: p. 64]. However, depending on the long-term objectives, the exact nature of the base can vary. For example, Roberts [Ref. 8] states a science base might emphasize "...long-range traverses for planetological studies or extension of observational capability with larger telescopes." [Ref. 8: p. 7] A production base, on the other hand, will incorporate highly automated systems to produce and transfer liquid oxygen for use in near-moon transportation systems. Lastly, a self-sufficient emphasis will include advanced research in utilizing indigenous materials for base extension. It is important to note that the production and self-sufficiency scenarios require a space station in low lunar orbit or an Earth-Moon libration point to provide a node for personnel transfer, refueling operations, and maintenance of the lunar lander/launcher and OTV. [Ref. 8: p. 9]

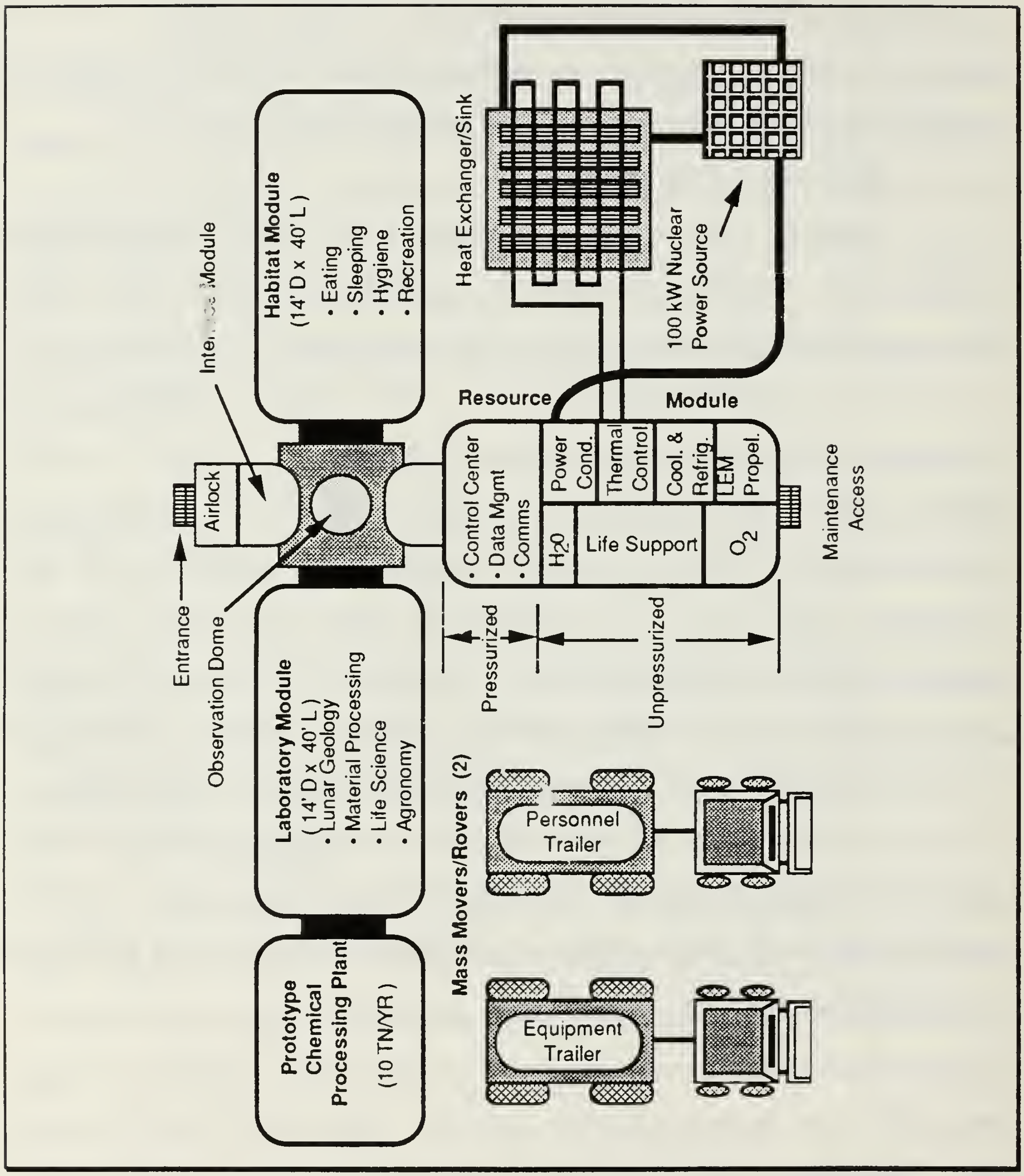


Figure 3.4 Initial Base Concept Plan View

TABLE 14. INITIAL BASE DEPLOYMENT STRATEGY

No.	Mission Description	Personnel		LEM Status*		No. of People On the Moon*
		Going	Returning	In LLO	On Surface	
1	Deploy interface module and power plant	0	0	1	0	0
2	Deploy laboratory module	0	0	1	0	0
3	Deploy habitat module and processing plant	0	0	1	0	0
4	Deploy resources module	0	0	1	0	0
5	Deploy second LEM	0	0	2	0	0
6	Send 1st construction team	4	0	1	1	7
7	Send 2nd construction team	3	0	1	1	7
8	Switch 1st construction team and 1st station team	4	4	1	1	7
9	Switch 2nd construction team and 2nd station team	3	3	1	1	7

4. Advanced Base

The advanced self-supporting phase of development is Phase IV. This stage is the terminal phase for the science and production scenarios. Future growth in Phase IV occurs by enlarging the number of experiments or products produced on the Moon. Note that a self-sustaining capability is not included in this phase. Specifically, the advanced lunar base would still not be self-reliant enough to permit severing the umbilical to Earth; however, its productive value

has increased, while its support requirements have decreased. A base concentrating on production will develop towards a highly automated state where permanent occupancy becomes unnecessary. In the production and science scenarios, the base begins to pay for its own operational costs in this stage. [Ref. 8: p. 7]

There is one additional phase which only applies to the self-sufficiency scenario. The advanced self-sufficient base, Phase V, is the final phase of the scenario directed towards a permanent manned presence beyond Earth. In this stage Roberts [Ref. 8] defines the lunar base as a "...truly autarkic settlement, a lunar colony, in which the link to Earth can be discretionary." [Ref. 8: p. 7] Figure 3.5 [Ref. 8: p. 8] illustrates the overall phased development and relates the approximate population base, technologies, and capabilities.

5. The Evolution of the Program

Figure 3.6 [Ref. 11: p. 67] relates lunar base growth and the development of lunar resources to support the transportation system. Initially, the base is totally dependent on terrestrial supplies. Seven kilograms in LEO is required for one kilogram delivered to the lunar surface. With the introduction of lunar oxygen, for operations near the Moon and return trips to Earth, the slope of the curve decreases from 7:1 to 3.5:1. As lunar manufacturing capability increases to the point where aerobrakes can be manufactured, the slope decreases to 1:1. There is difficulty in calculating the specific value of lunar products at this time. "Lunar credit," shown in Figure 3.6, is at the point where a closed ecological life-support system (CELSS) and significant manufacturing capabilities are available. The slope of the "credits" line is a function of the amount of oxygen required to support non-lunar activities, the value and quantity

of lunar resources required in LEO, and the less tangible value of research gained by the lunar base. The dashed line of constant slope(7:1) indicates the continued total dependency that would exist if these technologies were not pursued on the Moon. This would be the case if elements of self-sufficiency were excluded in the strategy of a lunar base program.

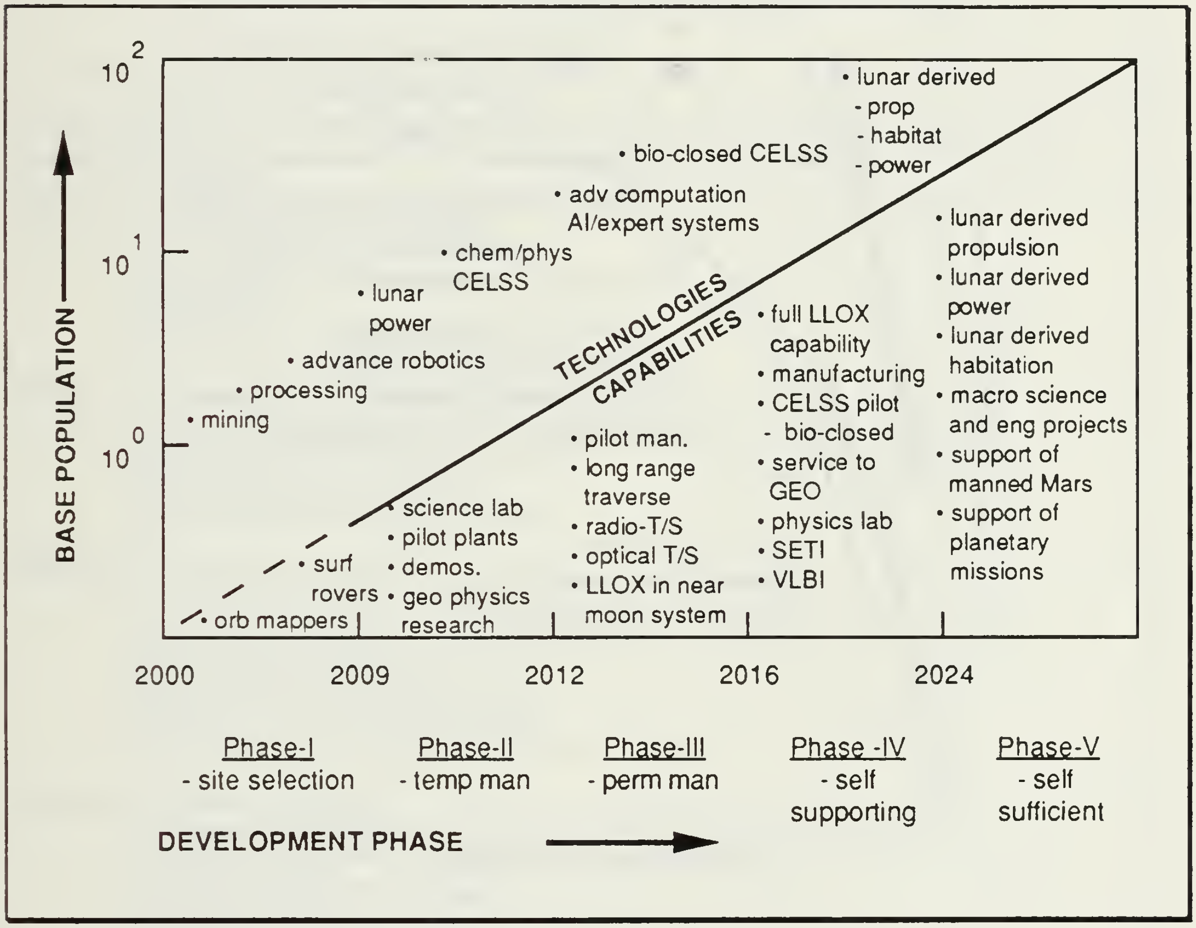


Figure 3.5 Phased Development of a Lunar Base

To summarize the stages of phased development associated with the three lunar base scenarios, the following tables are presented: Table 15 [Ref. 11: p. 64] depicts the growth phases of a science base scenario, Table 16 [Ref. 11: p.

65] presents the stages of a production base scenario, and Table 17 [Ref. 11: p. 66] describes the evolution of a base oriented towards self-sufficiency.

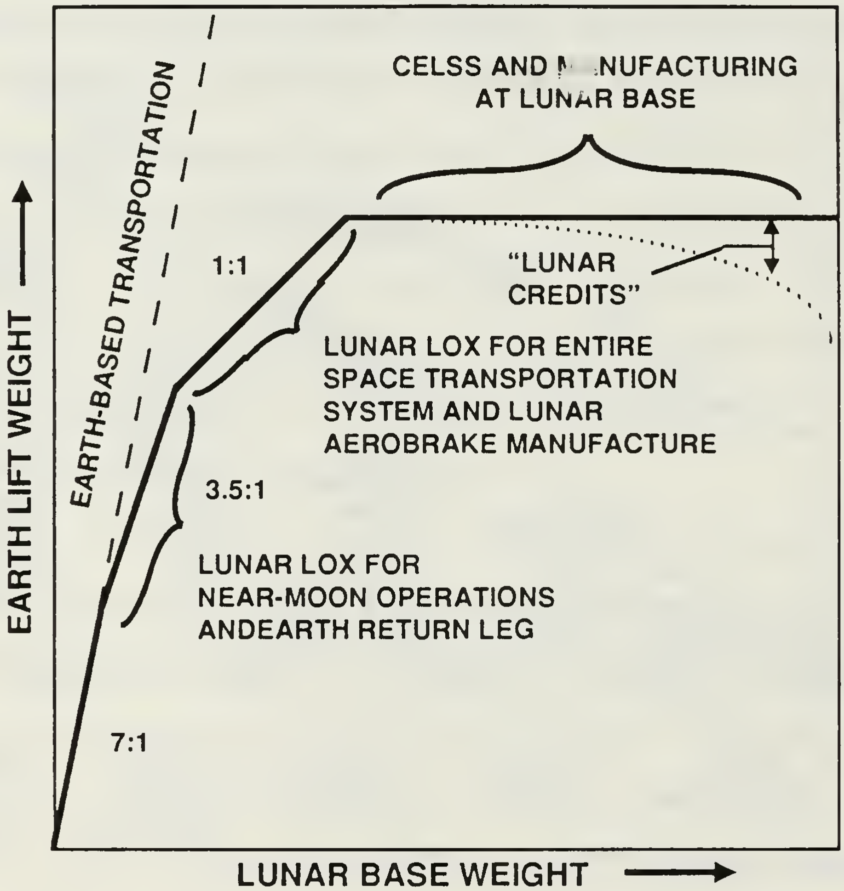


Figure 3.6 Earth Lift Weight Versus Lunar Base Weight

TABLE 15. SCIENCE BASE SCENARIO

A growing capability to do lunar science and to use the Moon as a research base for other disciplines, using lunar resources to a limited extent to support operations.

Phase I: Preparatory Exploration

- Lunar orbiter explorer and mapper
- Instrumentation and experiment definition
- Site selection
- Automated site preparation

Phase II: Research Outpost

- Minimum base, temporarily occupied, totally resupplied from Earth
- Small telescope/Geoscience module
- Short range science sorties
- Instrument package emplacement

Phase III: Operational Base

- Permanently occupied facility
- Consumable production/Recycling pilot plant
- Long range science sorties
- Geoscience/Biomedical laboratory
- Experimental lunar radiotelescope
- Extended surface science experiment packages

Phase IV: Advance Base

- Advance Consumable production
- Satellite outposts
- Advance geoscience laboratory
- Plant research laboratory
- Advance astronomical observatory
- Long-range surface exploration

TABLE 16. PRODUCTION BASE SCENARIO

A lunar base that is intended to develop one or more products for commercial use. Manned activity may be continuous, but a high degree of automation is expected

Phase I: Preparatory Exploration

- Lunar orbiter explorer and mapper
- Lunar pilot plant definition
- Site selection
- Automated site preparation

Phase II: Research Outpost

- Minimum base, temporarily occupied, totally resupplied from Earth
- Surface mining pilot operation
- Lunar oxygen pilot plant
- Lunar materials utilization research module

Phase III: Operational Base

- Permanently occupied facility
- Expanded mining facility
- Consumables supplied locally
- Oxygen production plant
- Lunar materials processing pilot plant(s)

Phase IV: Advance Base

- Large scale oxygen production
- Ceramics/Metals production facility
- Locally derived consumables for industrial use
- Industrial research facility

TABLE 17. SELF-SUFFICIENCY SCENARIO

A lunar base that grows in its capacity to support itself and expands its capabilities utilizing the indigenous resources of the Moon, with the ultimate objective of becoming independent of Earth.

Phase I: Preparatory Exploration
- Lunar orbiter explorer and mapper
- Process definition
- Site selection
- Automated site preparation

Phase II: Research Outpost
- Minimum base, temporarily occupied, totally resupplied from Earth
- Surface mining pilot operation
- Lunar oxygen pilot plant
- Closed systems research module

Phase III: Operational Base
- Permanently occupied facility
- Expanded mining facility
- Lunar agricultural research laboratory
- Lunar materials processing pilot plant(s)

Phase IV: Advance Base
- Lunar ecology research laboratory
- Lunar power station-90% lunar materials-derived
- Agricultural production pilot plant
- Lunar manufacturing facility
- Oxygen production plant
- Lunar volatile extraction pilot plant

Phase V: Self-sufficient Colony
- Full-scale production of exportable oxygen
- Volatile production for agriculture, Moon-orbit transportation
- Closed ecological life support system
- Luna. nanufacturing facility: tools, containment systems, fabricated assemblies, *etc.*
- Lunar power station-100% lunar materials-derived
- Expanding population base

E. LUNAR INFRASTRUCTURE

Establishing a lunar infrastructure to support human habitation and productivity on the Moon is a vital task. Building a lunar infrastructure can be viewed as an investment, however. The process requires a large amount of resources from Earth, but once the infrastructure is in place, the demands on further terrestrial support can be reduced. Koelle *et al.* [Ref. 5] define infrastructure as "...a complex of hardware, software, and operating procedures that make it possible for organized human activities to be carried forward." [Ref. 5: p. 473] Hence, the lunar infrastructure is analogous to a machine handling information, energy, and matter. As shown in the previous section, the process is evolutionary in nature, proceeding from a limited capability and expanding over time.

At the outset, the infrastructure will consist of a power plant, habitat, experimental modules, and a limited support crew for construction and transportation purposes. At this early stage, power requirements will be in the range of 500 kW to 1 MW. Information processing will be in the $\frac{\text{Gbit}}{\text{sec}}$ range within the lunar base and in the $\frac{\text{Mbit}}{\text{sec}}$ range between the lunar base and Earth. The processing of material will be limited to recycling for life-support and agricultural research experiments. If stable operations are sustained by the initial encampment, crew replenishments maintained, and Earth supplies delivered, the lunar infrastructure will grow. Soon multi-MW electrical power will be available. Multi-ton daily handling of matter will be the norm. Robotics and artificial intelligence will be common. A complex series of roadways will be built. An extensive power grid will be established. Finally, small lunar outpost

settlements will begin to appear, separate from the original lunar base. [Ref. 5: pp. 473-474]

1. Surface Transportation

The development of the road networks requires early efforts. Surface transportation is a key element to the entire lunar infrastructure. The construction of a surface transportation sub-system will be a lengthy process considering that the equatorial circumference of the Moon is about 10,000 kilometers. A multiply-connected network might be over 100,000 km in total length. At the current time, it is not clear if an extensive road network is desirable. The preferred means of conveyance depends on transportation requirements, physical boundary conditions, and economics. Possible candidates include chemical rockets, electric cars, magnetically levitated trains, mass drivers, and tracked vehicles. As an initial means of transportations, wheeled and tracked vehicles are most likely. As soft and hard roads develop, the travel speed will increase while the energy consumption decreases. Ultimately, the time to travel between destinations will decrease. [Ref. 5: p. 474]

2. Developing the Technology

Although a vast amount of operational experience and technology breakthroughs were gained from the Apollo project, much research is still required in every aspect of the lunar base infrastructure. Table 18 [Ref. 5: p. 476] lists the technology required from the initial base stage to the self-sufficient settlement stage. Current research efforts will be discussed later in this thesis.

F. ALTERNATIVE CONCEPTS

This section will contrast two alternative concepts distinctly varying from the proposed configurations of the previous sections. First, a polar base location site

will be evaluated. Secondly, a remotely operated lunar base functioning as an interim step to a permanently manned base will be analyzed.

TABLE 18. TECHNOLOGY REQUIREMENTS

Base	System/technology	Early base	Mature
Space transportation			
	Earth to orbit-heavy lift vehicles	x	x
	Orbital transfer vehicles	x	x
	Space ports		
	Earth orbit	x	x
	Lunar orbit	–	x
	Low thrust propulsion	–	x
	Lunar landers (cargo and human-rated)	x	x
	Lunar launch facility	x	x
Lunar surface infrastructure			
	Nuclear power plant	x	x
	Solar energy conversion		
	Terrestrially fabricated	x	
	Lunar fabricated		x
Habitation modules			
	Modified space station modules	x	
	Utilizing lunar materials		x
Lunar mobility			
	Short range, electric rovers	x	x
	Long range, fixed bed	–	x
Construction, mining equipment			
	Simple (loaders, cranes, trucks)	x	
	Complex	–	x
Special purpose equipment/facilities			
	Scientific experiments/laboratories		
	Apollo and space station derivatives	x	
	Special purpose, utilizing indigenous materials		x
	Materials processing plants		
	Chemical extraction	x	x
	Solar thermal/processing	–	x
Manufacturing/fabrication			
	Simple	x	
	Complex		x

1. A Polar Base

This sub-section will discuss the possibility of locating a lunar base at either of the Moon's poles. First, the polar environmental conditions will be

specified. Then, a possible habitat design and description will be analyzed. Finally, the advantages and disadvantages of a polar location will be evaluated. Additional considerations are given in Appendix A.

a. The Polar Environment

The Moon's polar axis is inclined 1.5° off the normal of the ecliptic plane. As a result, no seasons are present on the Moon. Near the poles, some portions of the landscape, like crater bottoms, are permanently dark. On the other hand, Burke [Ref. 12] discusses the possibility of some portion of the solar disk being continually above the horizon. Such a finding would have extremely important ramifications for decisions of site selection and will be discussed shortly. [Ref. 12 : p. 77]

The best photographs of the Moon's poles were taken from Lunar Orbiter IV in 1967. These photographs had a resolution of 100 meters. Topographical features of both poles were rugged, depicting a heavily cratered highland region. By comparison and analogy with Apollo data, the poles are believed to be composed of lunar highland rocks and soil vice mare type composition. Unfortunately, industrial resources peculiar to maria may not be abundant near the poles. [Ref. 12: p. 78]

At the lower latitudes, a twilight haze detected by both Soviet and U.S. spacecraft exists. This haze may be due to small particles moving in electrostatic suspension within a few meters o: the surface. Additionally, this twilight haze is associated with terminator passage (sunrise and sunset). Since such a condition is constantly present in the polar regions, the local environment may be more complicated than first envisioned. This twilight phenomenon must

therefore be considered when placing astronomical instruments in areas requiring minimum scattered light. [Ref. 12: pp. 78-79]

Another important unknown is the presence or absence of polar ice on the Moon's surface and subsurface. The low temperature (perhaps as low as 30 to 40 K) raises the prospects of trapped water and fossil ice surviving in this lunar environment. There is no way to determine this presence other than by lunar surface exploration (including drilling). [Ref. 12: p. 79]

Burke further cites other advantages of a polar location. Perhaps the most dominant consideration of habitat design is the constant thermal and illumination environment. Anywhere else on the Moon, the lunar day-night cycle lasts two weeks. To cope with such long days and nights, complex systems are required to compensate for problems of power, thermal insulation and illumination. Unfortunately, the frailty of man makes the human element the weak link of the entire system. All factors considered, a polar location would simplify the overall necessities of the lunar base. Thus, by simplifying various critical systems, the reliability of components increases, and several possible sources of failure are removed. [Ref. 12: pp. 79-80]

b. A Polar Habitat

Figure 3.7 [Ref. 12: p. 81] illustrates one conception of an underground polar habitat. Depicted is the nearly horizontal sunlight beam used as a source of warmth and illumination. Heliostat mirrors direct the solar beam into a periscope-like tunnel. The shape and configuration of the reflector elements provides shielding against cosmic and solar ionizing radiation. Within the habitat, other mirrors direct the sunlight as desired, eliminating some energy conversions otherwise required for illumination. [Ref. 12: pp. 80-81]

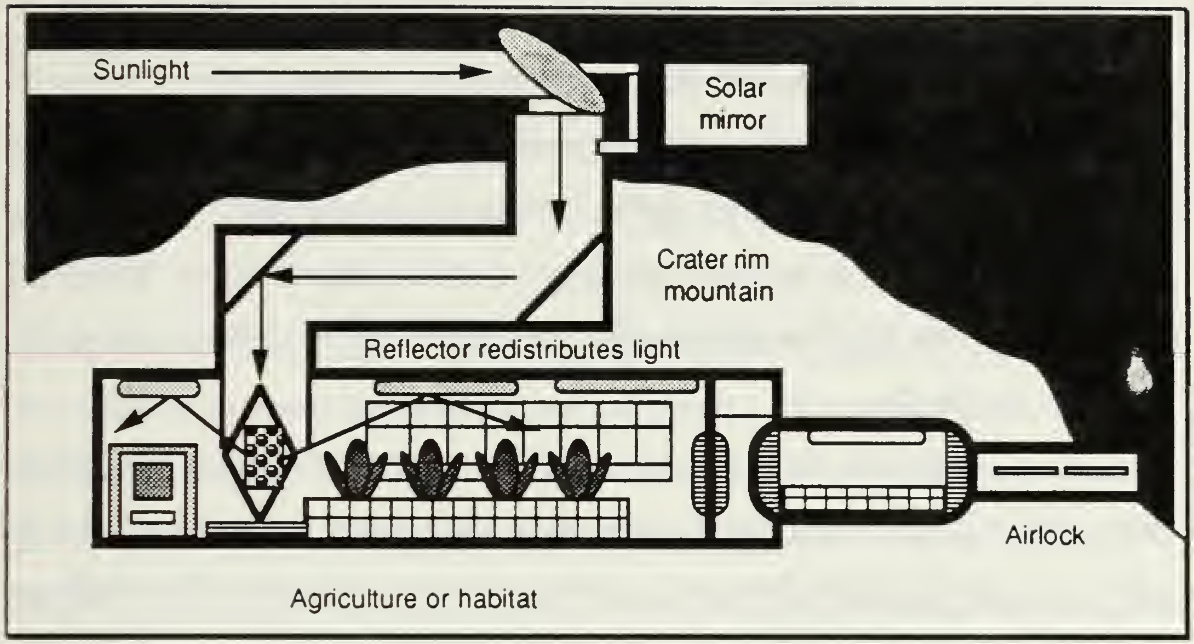


Figure 3.7 Underground Polar Habitat

c. Advantages and Disadvantages

A possible source of energy could be obtained from a "Solar Tower" configuration. This apparatus consists of a base which rotates at one-half degree per hour. As a result, the tower is continuously oriented toward the sun. Installed on the tower are heliostat mirrors for a solar furnace, a cylindrical collector for lower temperature heat, and a solar photovoltaic panel. Such a system could provide the base with a constant energy supply and a small reserve power plant to handle solar eclipses (whose duration time is typically two hours). The problem of heat rejection becomes simplified by constructing a surface radiator oriented to space and insulated on its bottom portion by a cold, permanently shadowed crater bottom. [Ref. 12: p. 81]

Another advantage the polar regions could offer is the storage capability of cold products in shadowed craters. The utility of this concept can play a vital role in solving stowage problems of oxygen reserves (for life support

or propellant needs). The entire storage process can therefore be simplified. Astronomy applications include the construction of a cryogenic telescope located in continual darkness. Quick access to and from lunar orbit results with a polar base site selection. At low lunar orbit, a space station or satellite crosses the pole every two hours. A polar orbit also gives access to the entire surface of the Moon and would facilitate the schedule of routine and emergency transports. [Ref. 12: pp. 81-82]

There are, however, several disadvantages of a polar site. First, most of the surfaces will remain dark since the glaring sun will maintain its relative position near the horizon. At the pole, Earth will hover from side-to-side and up-and-down a few degrees (lunar librations), but will remain below the horizon for nearby regions. Therefore, communications to and from Earth will require orbital or surface relays. These relays are practical, but consideration must be given to preserve the radio silent environment of the lunar far side if radio astronomical observations are to be conducted. Fiber optic cables may also be a viable solution. [Ref. 12: p. 83]

The disadvantages of living at the poles can be overcome and are outweighed by the advantages to be gained [Ref. 12: p. 83]. However, the Moon's poles require further orbital and surface exploration prior to any decision for site location. Only actual expeditions to the poles will definitively answer whether or not a lunar polar base is desirable.

2. Remotely Operated Base

This sub-section will discuss a remotely operated base. The motivation for this type of base will be analyzed, alternatives to a manned lunar base will be listed, and the advantages of a remotely operated base will be specified.

a. *Motivation*

Barrett [Ref. 15] has investigated the possible role of remotely operated lunar base serving in the capacity as an interim step in space development. He maintains that such base could provide access to lunar resources between ten and twenty years prior to any economically feasible manned lunar base. Possible research could include the study of growth and the development of plants and animals in lunar gravity. The evaluation of industrial equipment designed for use on the Moon could also be accomplished. Various techniques for lunar construction could be developed and evaluated on site. The weight for a remotely operated base would be considerably less than that required for a manned mission. Finally, current launch vehicles could be utilized for logistics support instead of developing new heavy-lift vehicles. [Ref. 15: p. 354]

b. *Alternatives*

Barrett furthers his case by stating the prospects of establishing a manned lunar base in the foreseeable future are uncertain. He cites budgetary difficulties experienced by the far less expensive shuttle and space station, and concludes the undertaking of a lunar base will not be initiated by the U.S. during the twentieth century. He further implies political factors will not make a lunar base viable until the early decades of the twenty-first century. [Ref. 15: p. 354]

Barrett, however, does offer three alternatives to establishing a manned lunar base:

- to abandon further activities on the Moon for an extended period-- the policy of the past 15 years
- to proceed with isolated manned or unmanned missions for lunar exploration and research

- to establish a remotely operated lunar base as an interim measure to permit continued progress toward lunar development pending the resumption of manned lunar operations. [Ref. 15: p. 354]

The first alternative leaves much to be desired and is not a goal of space development. The second alternative advocates independent missions located at separate and isolated sites. The third alternative proposes an unmanned, permanent lunar base option. Barrett offers several arguments in support of a permanent base over independent missions.

c. Advantages

The first important advantage deals with logistical requirements. A permanent base has the availability of consolidated support services and facilities located within a central location. Some of these facilities include:

- landing fields
- surface transportation
- electrical power
- communications equipment

Secondly, cost and weight requirements of the base would be reduced. Finally, conducting operations at a permanent location creates the opportunity for each mission to incrementally contribute to the growing capability of the base. Such capabilities include the capacity to perform scientific research and engage in productive enterprise. [Ref. 15: pp. 354-355]

Barrett further explains that telerobotics would be the principle means of conducting operations at a remotely operated lunar base. Small-scale robotics or teleoperated systems would have more immediate prospects for implementation on the Moon. The primary activity of the lunar base would be oriented towards the evaluation of industrial equipment and the manufacture and

testing of products derived from lunar materials. An eventual goal would be the establishment of small pilot plants as engineering models. As a result of these prototype plants, a small quantity of commodities would be manufactured. It is important to remember, however, large-scale manufacturing is not an immediate objective. [Ref. 15: p. 355]

G. ENVIRONMENTAL CONSIDERATIONS

Most lunar scientific research activities require the unique lunar environment to be preserved. Lunar base operations may affect the environment in adverse ways, especially if industrial facilities expand. For example, because the entire lunar exosphere weighs only ten kilograms, the atmospheric pressure of the Moon could actually change as a side-effect of lunar operations. Rockets or industrial activities have the potential to coat the entire surface with thin layers of effluents. Some of these effluents, like water vapor or carbon-based chemicals, will boil off at low altitudes, but may also be trapped in permanently dark craters near the polar regions. Eventually, the atmospheric composition may change for the worse, thus compromising the pristine observing conditions desired by astronomers. High levels of contamination could even degrade or destroy electrical and optical equipment. Effluents containing radioactive elements could interfere with radioisotope methods for age dating lunar samples. Furthermore, industrial activities propagate seismic noise and complicate seismic research. Orbiting debris from spent rockets or satellites could pose a potential hazard. Additionally, extensive satellite communications networks might increase the radio noise background inherent to the far side of the Moon. Considering the adverse effects of manned activity listed above, a means for studying and controlling lunar pollution should be planned and implemented.

The designation of certain areas as scientific reserves may be a viable option. In the end, a lunar base can be a self-destructing source of pollutants which degrade or destroy research efforts. Careful consideration of the lunar environment is one design strategy common to all scenarios.

This chapter has dealt with alternative strategies for establishing a lunar base. A survey of concepts and notions proposed by leading authorities in lunar base research has been presented. The concept of a lunar base was defined, and program requirements were listed. Three scenarios emphasizing different goals were compared and contrasted. The distinct phases of lunar base development were differentiated. The characteristics of a lunar base infrastructure were specified. In addition, alternative concepts to the three scenarios were presented. Finally, environmental conditions and possible adverse effects of manned activity were listed. The next chapter will examine lunar base design and construction concepts.

IV. LUNAR BASE DESIGN

This chapter is divided into four sections. The first section introduces factors which influence the design concept of a lunar base. The second section examines the radiation concerns associated with the lunar environment. The third section outlines three possible base structures proposed by Land [Ref. 16]. The fourth section addresses the form and function of a Moon base. Additional material is provided in the appendices.

A. DESIGN CONCEPT

The design of a lunar base will employ the strategy discussed in the previous chapter. As such, the construction and growth of a base on the Moon will exhibit evolutionary characteristics.

1. Introduction

The initial base will be composed of small structures, simple in configuration. As materials and structural concepts are tested and evaluated, the base will expand accordingly. Concurrent with base expansion will be the utilization of lunar resources. This incremental and modular approach is in contrast with earlier proposals of lunar base design. These previous designs show finite and sizable structures built in one operation [Ref. 16: p. 363]. There is doubt regarding the technological capability of building such large structures (in thousands of meters) initially. Even if the capability exists, would there even be a need for these massive structures? In addition, the possibility exists that the design may be out-of-date by the completion of the complex structure. Appendix B indicates a possible need for a roof spanning 200 meters or more to house an

artificial gravity carousel. There is no doubt that a long-range physical development strategy must be planned and implemented. This strategy will guide the design and influence the initial configuration of the base. The evolutionary approach already mentioned permits benefiting from experience and will generate an orderly expansion reflecting incremental growth. Other factors which contribute to the overall expansion of the base include surface transportation, supply logistics, power, and centralized or decentralized design. [Ref. 16: p. 363]

2. First Generation Structures

Land [Ref. 16] has proposed several structures for the various stages of lunar base development. The first-generation structures will be the post-camp stage. For this phase, Land suggests a configuration of two independent parts: a pressurized enclosure under a separate radiation shielding canopy. The size and shape of the structure will be determined by the scope of operations within the individual enclosures. The canopies are necessarily heavy, and ultimately, should be derived from lunar resources. Pneumatic structures forming pressurized enclosures will be relatively lightweight and compact during storage. The small volume and weight is necessary if initial supplies must be transported from Earth to the Moon. [Ref. 16: pp. 363-364]

One main radiation shield consists of lunar regolith spread over a supporting framework and is raised above the lunar surface. The shield can also be expanded at the perimeter. The pressurized component is structurally independent of the canopy and is erected beneath the shield according to shape and volume constraints. Thus, part or all of the shielded space can be pressurized. Various heights are obtained underneath the shield by dropping the

floor level to the required elevation. Miscellaneous equipment such as telescopes and antennas can be mounted over the shield or staged in areas next to the shield. This overall concept proposed by Land [Ref. 16] is aimed at simplifying the general configuration, building technology, erection, and expansion of the lunar base. The chance of failure in building and maintenance operations can therefore be reduced. Finally, the need for heavy equipment required for construction is minimized. [Ref. 16: p. 364]

One of the primary influences in lunar base design is cosmic radiation. Land cites data dealing with lunar surface radiation levels. The annual dose equivalent due to cosmic rays at times of solar minimum is about 30 rem. This data indicates 1.5 to 2.0 meters of regolith is required to provide adequate shielding for personnel against cosmic and solar radiation effects. This quantity of lunar soil is sufficient in density to block radiation doses that would otherwise be encountered by workers on the lunar surface. The resulting radiation levels would be comparable to the dosages encountered by a terrestrial x-ray technician. Since this required thickness is not excessively prohibitive, Land asserts the viability of regolith supporting structures. To the maximum extent possible, lunar base operations will be conducted beneath the shield(s). The component(s) beneath the shield can be either a pressurized "shirt sleeve" environment or an unpressurized "suited" environment. [Ref. 16: p. 364]

B. RADIATION CONSIDERATIONS

The design proposals presented by Land [Ref. 16] for radiation shields and regolith-supporting structures are based on generally accepted data for radiation levels and regolith density. However, he states there is a possibility that the figures may be too low. In particular, the hazards associated with secondary

neutrons have not been addressed. These secondary neutrons are generated within the shielding material by cosmic rays. In addition, "storm cellars" with excessive regolith shielding must be constructed to provide safe haven during occasional solar flares. If a great increases in regolith thickness were required as a result of the considerations mentioned above, the support structure may prove to be uneconomical. Land [Ref. 16] states that the requirement for greater regolith thickness may be more economically pursued by tunnel or cavern design concepts. Needless to say, radiation levels and regolith density are crucial issues affecting lunar base design. [Ref. 16: p. 364]

1. Lunar Base Layout

Various tasks will be accomplished by unshielded personnel on the lunar surface. The duration is limited by radiation exposure measured as accumulated dose over time. This exposure consists of high-level radiation during high-intensity, unshielded surface activity as well as low-level radiation accumulated beneath the shield. To maximize the permissible exposure time, radiation doses must be minimized. As a result, all components of the base should be consolidated under one shield. This arrangement would eliminate radiation accumulated by personnel transiting between different installations in an otherwise fragmented base. Furthermore, the effectiveness of the shield should be maximized. Some parts of the base must necessarily be separated from the main installation due to operational and safety considerations (for example, a nuclear power source). In these cases, the connecting inter-links must be shielded. Since the radiation flux is from all directions (except from below), the periphery of the shield must be protected by additional lunar regolith mass. To

enhance shielding efforts, entrances should be labyrinthine with over-lapping screened walls to effectively bar radiation. [Ref. 16: p. 365]

2. Solar Shielding Canopies

Land proposes solar shielding canopies to create or complete shade over walkways and vehicle paths linking various components of the lunar base which are separated from the main base shield. He suggests a horizontal canopy to provide total shade at lunar noon. The temperature in the shade would depend on the width of the canopy. In addition, radiative thermal transfer will occur through the ground near the edges of the canopy. Furthermore, Land suggests the canopies might be perforated with holes to facilitate illumination. The temperature would increase accordingly, depending on the size of the holes. [Ref. 16: p. 370]

3. Service Stations

As previously stated, the distance traveled by personnel on the lunar surface is limited by exposure time. Long distances traveled by slow moving vehicles could result in a potentially hazardous situation. As a result, in order to undertake lengthy transits, shielded service stations must be built at strategic locations. These service stations could provide radiation-free resting and sleeping facilities as well as re-supply and servicing capabilities. They may also serve as emergency shelters in case of solar flares. [Ref. 16: p. 371]

4. Solar Orientation

Solar orientation is an important consideration in the design of a lunar base. Since sunrise and sunset are relatively long and low-angled, energy build-up on steeply inclined surfaces may be considerable and should be considered in the design of a Moon base. In addition, the entrances and external operational

edges of the base complex should be oriented away from the sun to minimize temperature variations. The hostile environment of the Moon introduces new and challenging requirements in the lunar base layout scheme. Land offers three design options of feasible shield support structures. These options will be discussed and illustrated in the following section. [Ref. 16: p. 371]

C. BASE STRUCTURES

Three specific types of base structures will be categorized and evaluated based on construction techniques, complexity, and type of enclosures.

1. Flat Shield (Pressurized Enclosure)

The first design concept is a flat shield raised in sections with pressurized enclosures beneath. Figure 4.1 [Ref. 16: p. 365] presents an overall view of such a base and the associated expansion. The numbers in Figure 4.1 represent the following elements:

1. Regolith shielding
2. Perimeter expansion
3. Base entry through overlapping radiation barrier walls, from lunar surface equipment and installations "park"
4. Solar shaded links to other parts of the base
5. Shielded links to other parts of base
6. Ramp access to lower levels
7. Initial erection sequence

The structure supporting the regolith consists of floors supported by girders assembled in a lattice configuration. These girders are connected to columns which can then be erected in sections. The dimensions of the framework and the spacing of the columns are influenced by the function of the base and the constraints of the pressurized chambers beneath. The column

spacing is flexible and relatively large spans are feasible. This is due to the reduced gravity of the Moon. The resulting dead-load weight of the dry lunar soil is not prohibitive. [Ref. 16: p. 366]

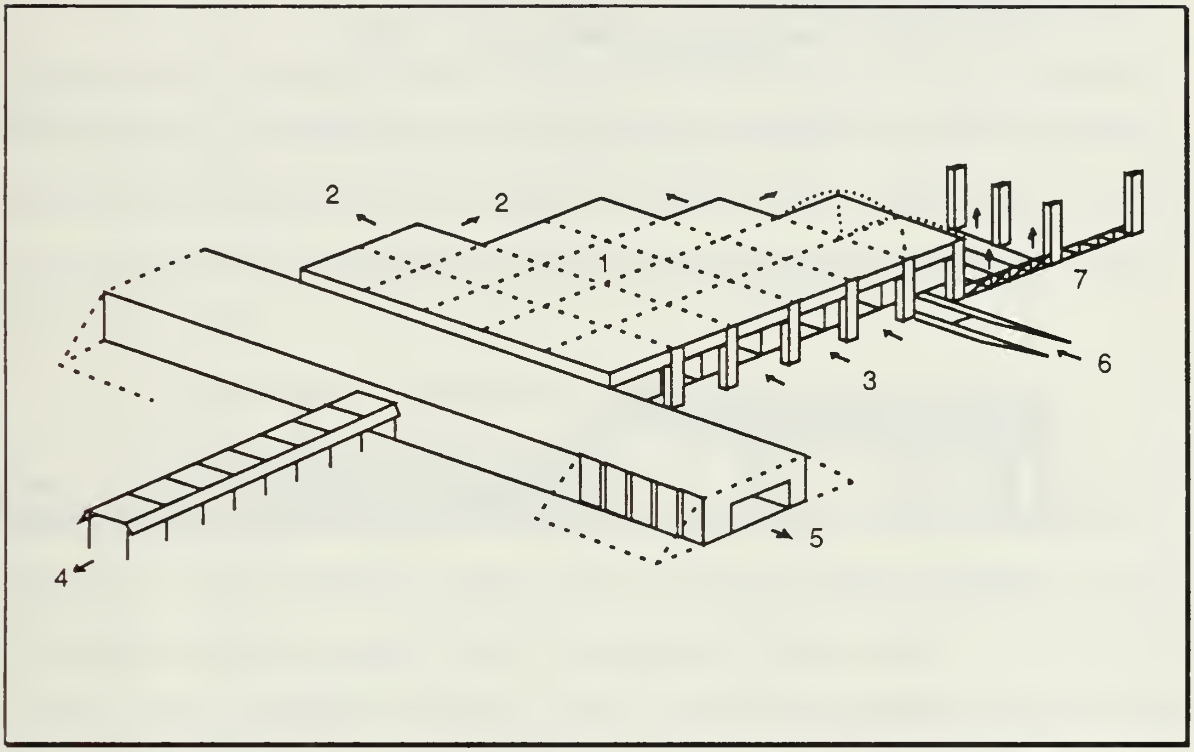


Figure 4.1 Base Concept I

The bays of the shield support structure are raised to the appropriate level by pneumatic jacks. The beams are then permanently connected to the columns. The regolith layer can be loaded either before or after the erection of the structure. Placing the lunar soil on the roof while still at ground level involves only pushing and leveling operations. Placing the regolith on the platform after erection results in more energy expended and requires additional equipment such as relocatable conveyor belts. The erection sequence is pictured in Figure 4.2 [Ref. 16: p. 366]:

1. Aluminum lattice girders and columns in place
2. Prestressed floors, employing molded regolith components
3. Floor loaded with regolith raised by jacks up column guide
4. Regolith leveled off
5. Entry through overlapping radiation barrier walls

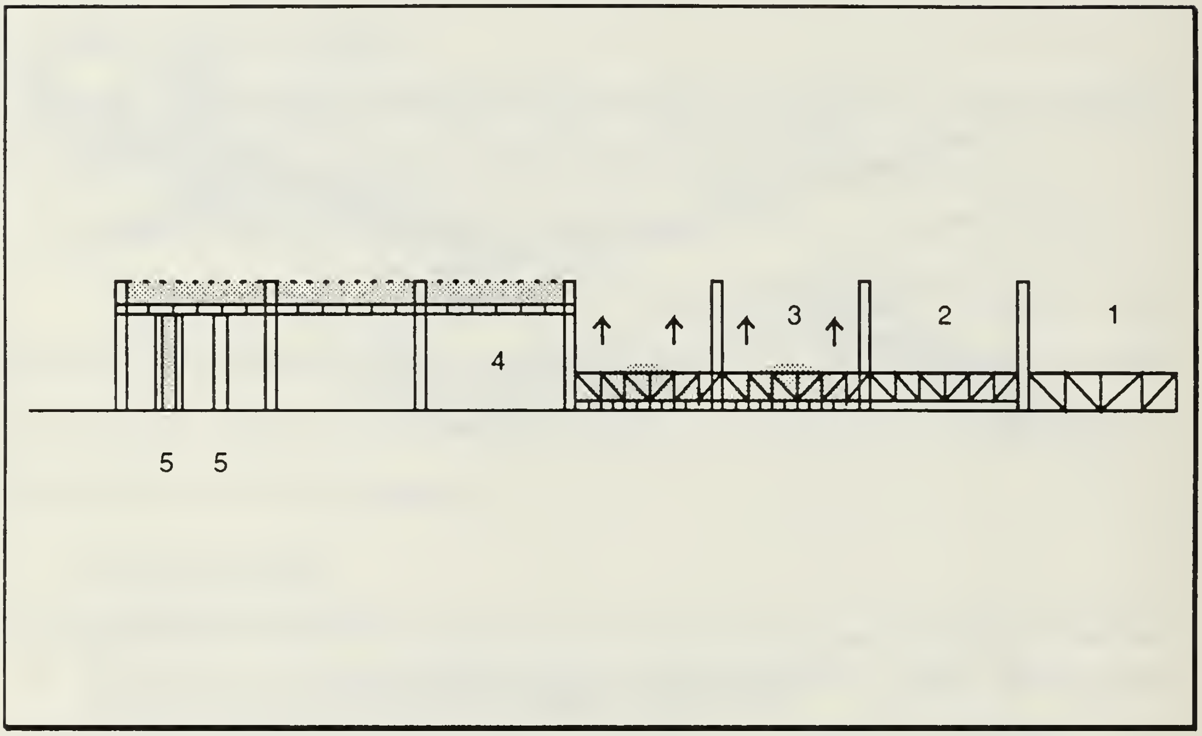


Figure 4.2 Base Concept I Erection Sequence

a. Prestressed Floors

The floors consists of regolith components molded together, prestressed from end to end with stranded fiberglass tendons. Stress is applied through the use of small handjacks. Segments are assembled flat on the leveled lunar surface. The tendons are then implanted and prestressed to form narrow floor sections. All sections can then be connected at the ends to the transverse girders. [Ref. 16: p. 366]

b. Folded Aluminum Floors

This alternative flooring scheme utilizes light weight aluminum segments. The folded aluminum sheet material is fabricated for maximum strength to weight ratio. In addition, the components are segmented for efficient storage during transportation. The maximum length of a floor segment is determined by the dimensions of the transporting vehicle's cargo bay. Initially, terrestrial flooring material transported from Earth will be used. Later, as lunar production plants are established, precast regolith components can be utilized. [Ref. 16: p. 367]

c. Pneumatic Component Floors

This final flooring alternative would employ inflatable beams, much like those already used by the military to enable trucks and tanks to cross craters and gullies. These inflatable beams consist of large diameter long tubes, smaller cross tubes and an aluminum deck covering the entire surface. As with the previous case, terrestrial materials would be used initially until lunar production was established. [Ref. 16: p. 367]

2. Low Arch Shield (Pressurized Enclosures)

The second design concept employs a low arch to support the regolith. If the arch is working in compression with no tensile stresses, then Land [Ref. 16] concludes no reinforcement is required. The components of such an arch will be made of molded regolith and assembled over a movable pneumatic support structure. The arches are erected in sections, each the width of the support structure, which shores several rings of the component members. After one section is in place and covered with regolith, the support structure is moved

forward to the next arch section. This is accomplished by partially deflating the structure prior to movement. [Ref. 16: p. 367]

Figure 4.3 [Ref 16: p. 367] illustrates the low arch shield design concept. The numerical labels correspond to the following :

1. Regolith shielding
2. Interlocking, molded regolith arch components
3. Movable pneumatic support form supporting arch assembly
4. Aluminum lattice girders to accommodate outward thrust of arches
5. Height increased, where required, by excavation
6. Expansion

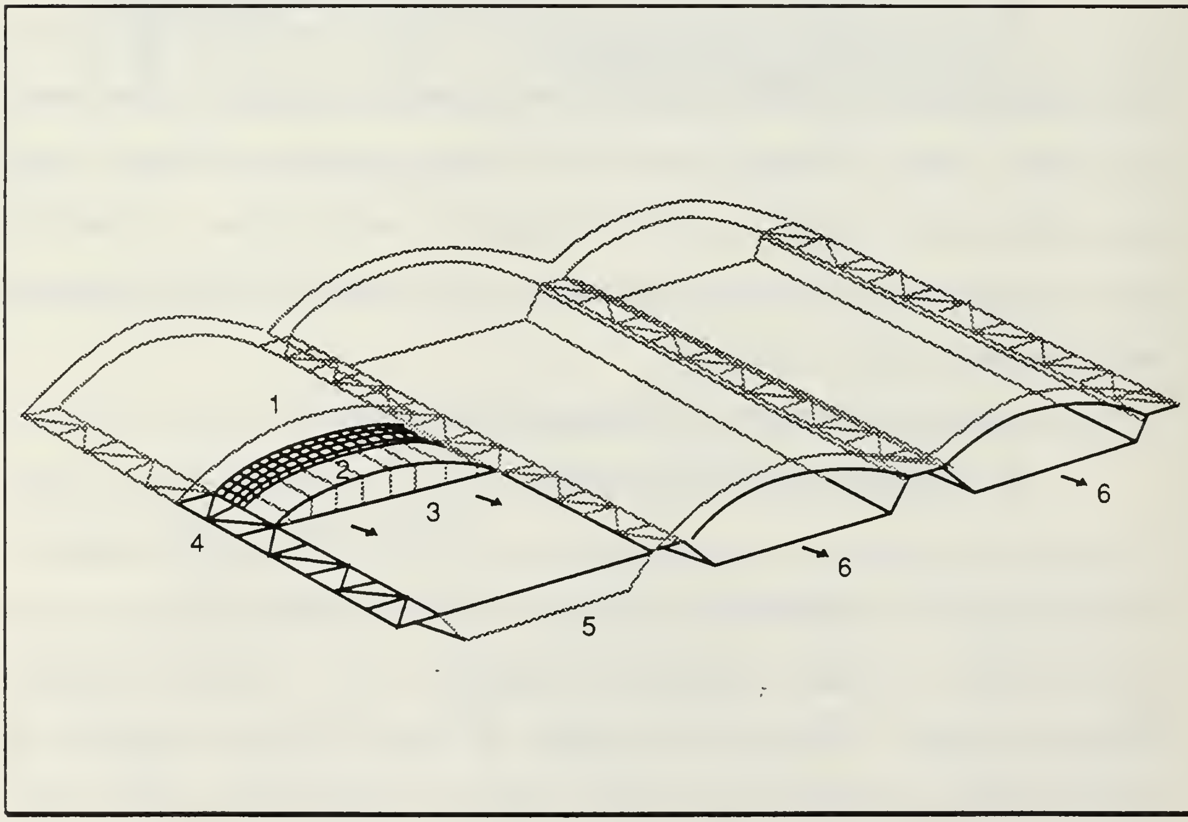


Figure 4.3 Base Concept II

The thrust of the arch is horizontal and is braced by two aluminum lattice girders. These girders are assembled from short sections laying flat on the level surface, one on each side of the arch. The girders are then anchored by spikes driven deep into the lunar surface. Alternatively, a transverse connecting cable can also be utilized for securing the aluminum girders. All girders are at a convenient depth and the cables are widely spaced. As with the first base concept, initial terrestrially manufactured elements of the arch could be quickly assembled to provide immediate protection from radiation. These elements must again be capable of efficient storage for compact and economical transportation. [Ref. 16: p. 368]

Land asserts that the weight and size of the prestressed floors as well as the compression arch shield will be determined by the lifting capability of two persons or applicable equipment. The design of the components will utilize a thin-rib, deep-section configuration to maximize stiffness and minimize weight. Components will be interlocking and self-aligning under stress. These components will be manufactured in a lunar plant from regolith and molded to the required configuration. Possible molding techniques include firing to the necessary temperature for sintering and surface sealing employing a direct solar or electrical furnace. Another option includes the use of a double-mix epoxy cement to bond regolith aggregates. [Ref. 16: p. 368]

Figure 4.4 [Ref. 16: p. 368] depicts a side view of the low arch concept. The numbers correspond to the following components:

1. Inflated arch support form
2. Interlocking, molded regolith arch components laid over inflated form

3. Regolith pushed over arch, pneumatic support form removed, excavated underneath where required by dragline scoop, and pressurized enclosures erected
4. Alternative pressurized enclosure using hermetic membrane applied to inner surface of shield
5. Interconnected arch shields with range of pressurized enclosures

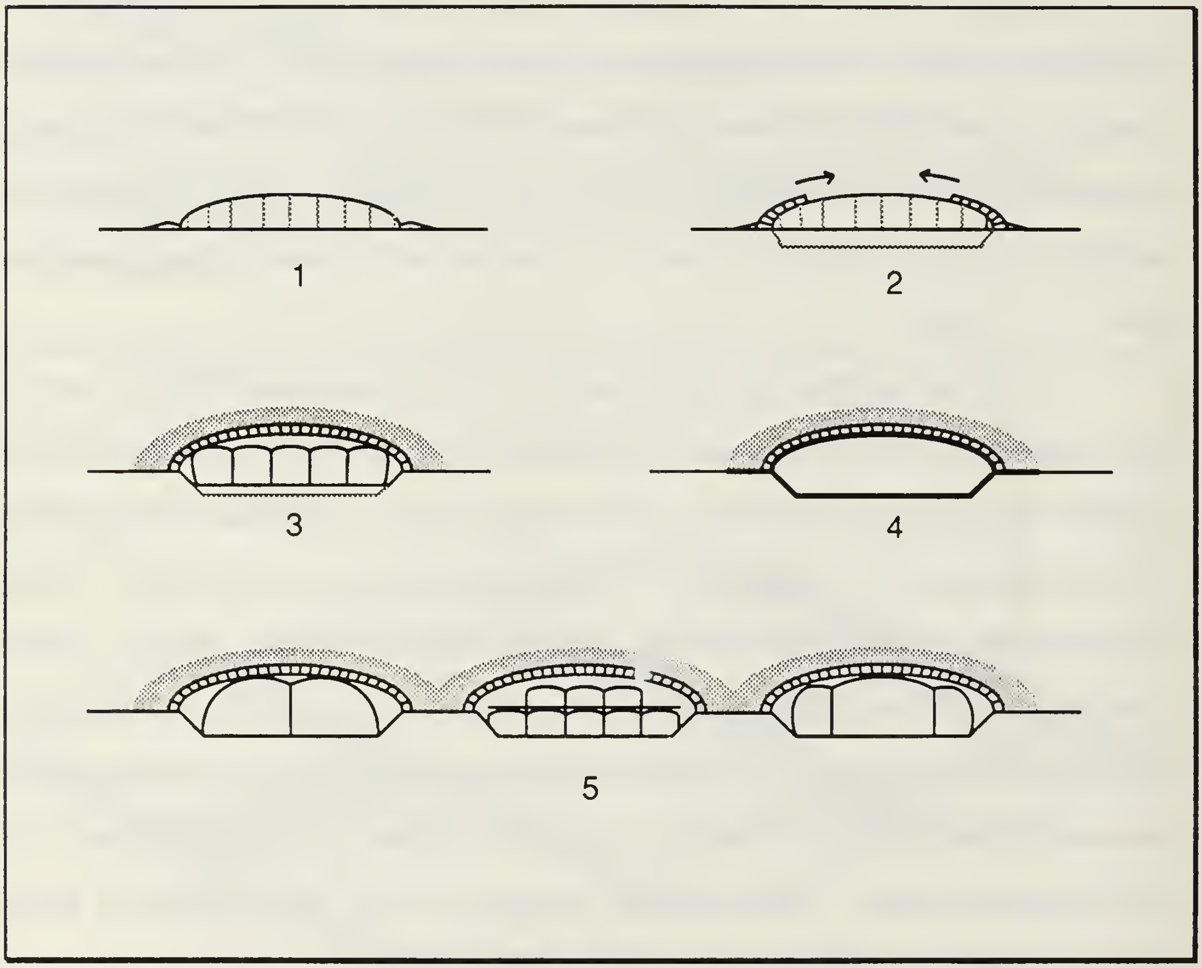


Figure 4.4 Base Concept II Side Profile

3. Low Arch Shield with Pneumatic Support Structure

In this concept, Land [Ref. 16] proposes a pneumatic structure to permanently support the regolith. The deflated structure is first spread over a level area of the lunar surface. Regolith is then pushed over the structure, and

then inflated. The raised regolith is leveled later or thickened where necessary. The upper surface of the structure is ribbed to hold the lunar soil in place. This concept can be applied in sections to form a continuous low arch or a single domed configuration. [Ref. 16: p. 369]

Figure 4.5 [Ref. 16: p. 369] illustrates this final concept. The numbered drawings correspond to the following descriptions:

1. Deflated pneumatic hybrid structure flat on ground, regolith pushed over
2. Structure inflated, raising the regolith
3. Plan showing concept applied in sections for a continuous low arch shield
4. Plan showing concept applied in a low, domed shield

D. FORM AND FUNCTION OF A LUNAR BASE

Functional considerations will determine the exact size constraints of the individual lunar base components. Presently, no specifications exist which delineates the range of activities of the anticipated base. Land recommends the formation of a small base planning group to "work in close collaboration with all specialized areas of the lunar base group to determine the dimensional characteristics of the base functions with their environmental servicing needs." [Ref. 16: p. 372] This functional itemization will influence base design, but the ultimate design will also be affected by the chosen building system and configuration. [Ref. 16: p. 372]

According to current estimates, some large-span enclosures will be needed for maintenance and assembly of large equipment. Examples of such large equipment include lunar surface vehicles and spacecraft, telescopes, and industrial machinery. However, a large portion of the base will probably consist of interconnected components, relatively small in dimension. Still, these

structures will be much larger than the initial camp stage modules and more economical to erect and maintain. Thus, both large- and small-area elements must be considered. [Ref. 16: pp. 372-373]

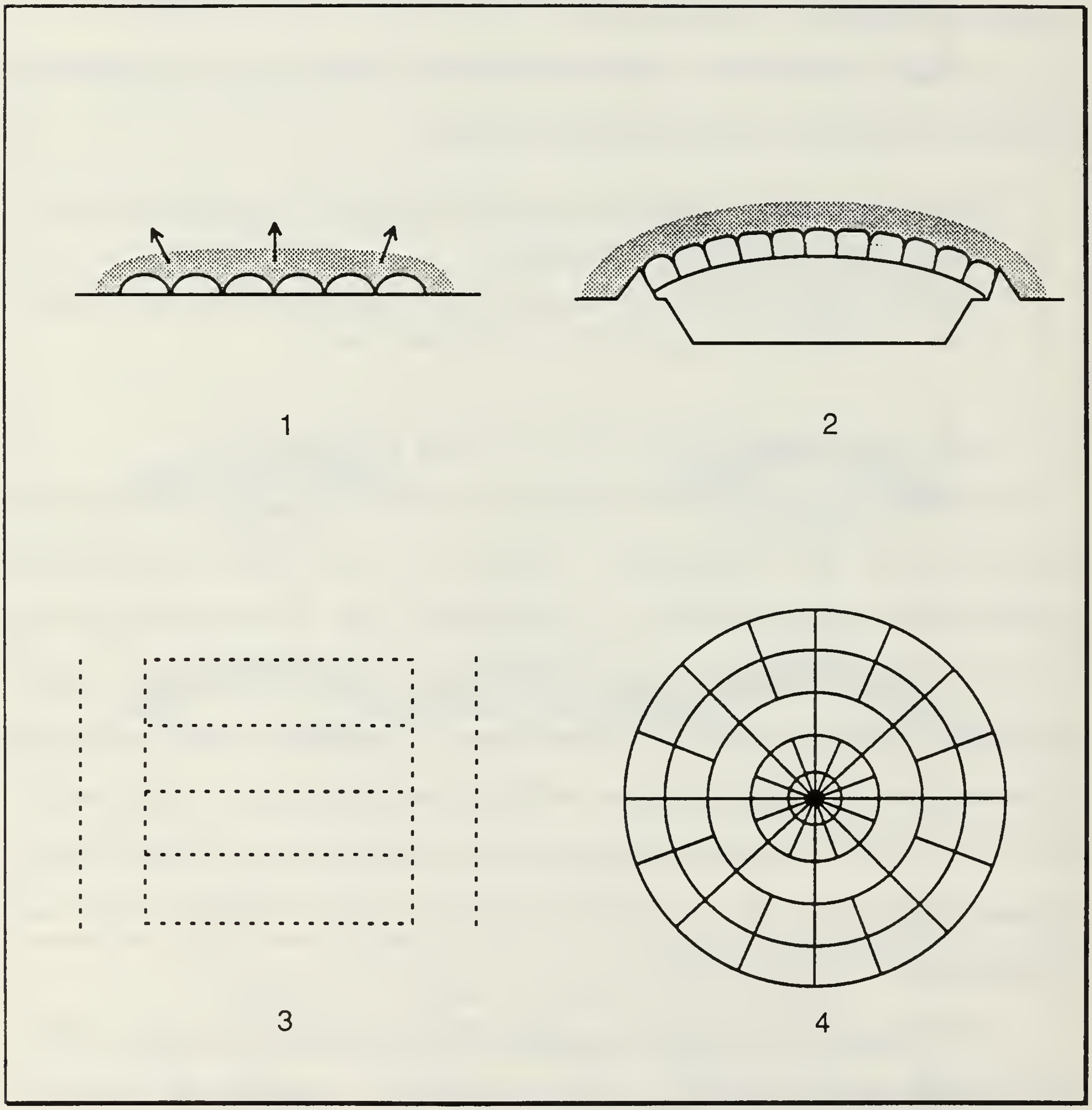


Figure 4.5 Base Concept III

Although the objective of the post-camp stage is to ultimately develop a lunar-based construction capability, some difficulty in the early stages can be

anticipated. Structures constructed for radiation shielding will use lunar regolith, but pressurization will generate tensile forces exceeding the strength of first generation regolith processing. Such processing is envisioned to include simple ceramic and glass block component manufacturing. Although limitations exist, structures with floor areas larger than previously available from the initial camp modules must be constructed. [Ref. 16: p. 373]

This chapter has considered possible design concepts for a lunar base. Three specific base structures have been described: (1) flat shield with pressurized enclosures beneath, (2) low arch shield with pressurized enclosures beneath, and (3) low arch shield with pneumatic support structure. In addition, radiation and solar considerations were examined. Finally, the form and function of a lunar base was discussed. The next chapter will present a brief overview of power considerations in establishing a Moon base.

V. LUNAR BASE POWER

This chapter is an introduction to potential sources of power for lunar base applications. Detailed analysis of each power system is beyond the scope of this thesis. Instead, a broad survey of possible power systems will be conducted in order to give proper perspective to powe' ssues. Power considerations will be placed in the context of overall program strategy discussed in Chapter III. Section A is an introduction to space power applications while Section B examines advanced power systems. Sections C and D elaborate on the current state of photovoltaic and advanced solar dynamic sources, respectively. Section E compares possible sources of nuclear power. Finally Section F details the possible role of superconductivity in lunar base applications. Additional material on solar power is included in Appendix A.

A. INTRODUCTION

The key element to exploration and development of lunar resources is energy. Chapter III listed the four stages of lunar development. Concurrent with this systematic progression is the required evolution of power systems. Power utilization by a lunar base will resemble terrestrial utility operations rather than energy-limited spacecraft [Ref. 17: p. 1]. Large-scale power requirements (hundreds of kilowatts or more) will primarily arise from industrial activities. These activities can be divided into three types of applications: material processing, propulsion requirements, and transmission needs. In a 1986 paper on lunar-based power systems, Criswell and Waldron [Ref. 17] depict potential power systems grouped into primary sources of power,

conversion means, energy storage devices, and delivery systems as summarized in Figure 5.1 [Ref. 17: p. 2]. The power sources are divided into those locally available, transport deliverable, or remote. Local solar power is obviously limited to daylight operation except at the lunar poles. Storage and conversion options can be segregated into two categories: those that can be primarily manufactured from available materials and those requiring significant input of terrestrial material. [Ref. 17: p. 1]

B. ADVANCED POWER SYSTEMS

There are four types of power systems applicable for space utilization in use or under development at the present time: Radioisotope Thermoelectric Generator (RTG's), photovoltaic, solar dynamic, and nuclear space power systems. RTG's have been utilized for planetary exploration missions and have a life expectancy of up to twelve years. The RTG's have a specific power of approximately four Watts per kilogram and are generally limited to low power applications of approximately 500 Watts. Photovoltaic (PV) power systems have been utilized on satellites with varying orbits, at power levels of a few kWe (kilowatts electric). Present PV systems can deliver 50 to 60 $\frac{W}{kg}$ if continuous sunlight is available. In low Earth orbit (LEO), energy must be stored in batteries when the satellite transits the dark side of Earth. The specific power drops accordingly, three to six watts per kilogram.

Solar dynamic (SD) power systems use concentrators to focus solar energy into high-temperature receivers. This energy is then used to heat the working fluid of a dynamic energy conversion system such as a Brayton, Rankine, or Stirling cycle system. Furthermore, this energy heats a thermal energy storage device (TES) material which provides heat for the dark portion of the mission.

Thermal energy is efficiently converted into electricity (20 to 30 percent) using the dynamic energy conversion. The excess heat is removed by a radiator.

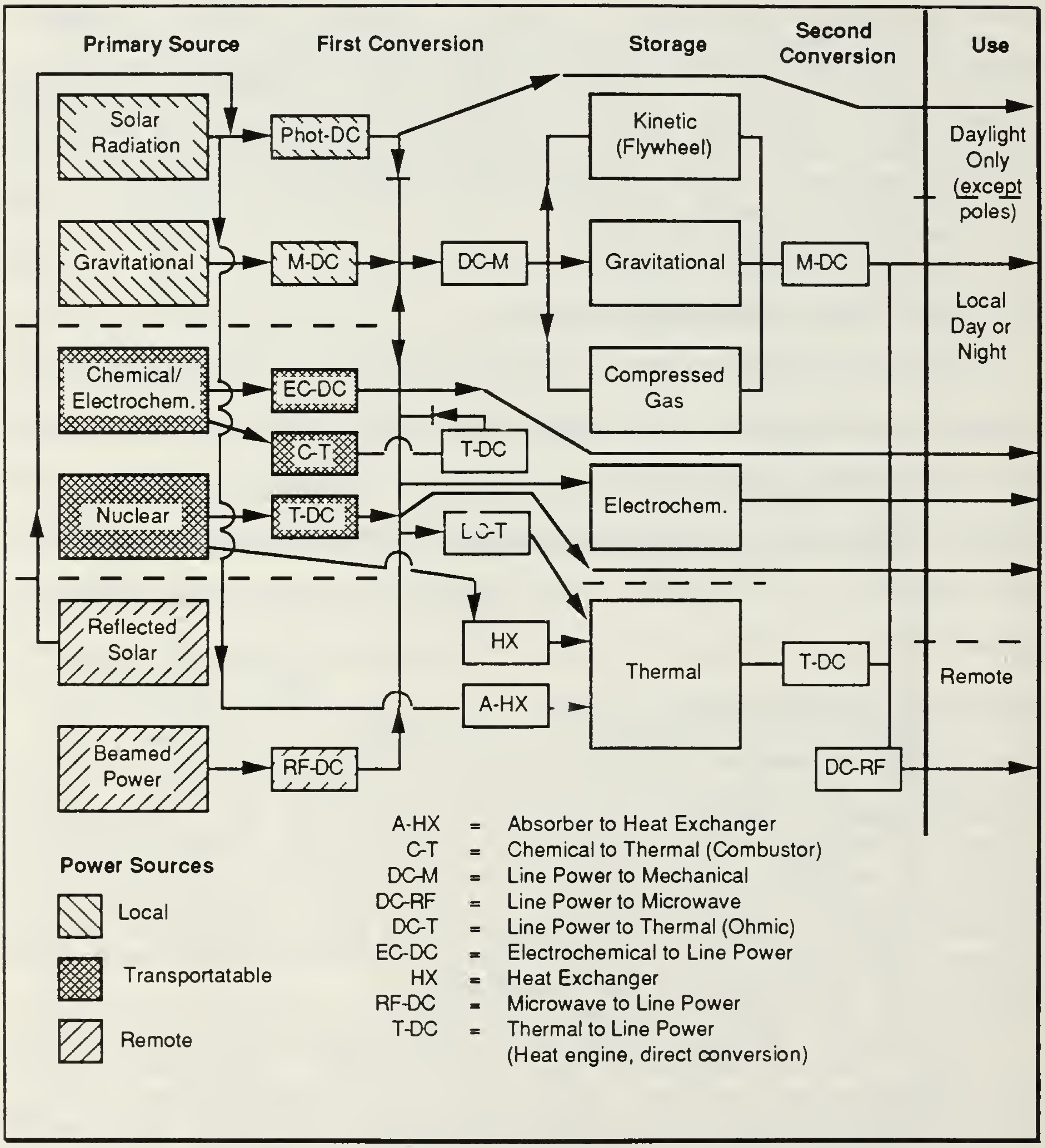


Figure 5.1 Possible Power Sources

In Nuclear Reactor Space Power Systems (NRSPS) the reactor provides thermal energy directly to an energy conversion system. Again, a high-temperature radiator is utilized to remove waste heat. Each of the mentioned power systems have potential use in lunar base applications. All have associated pros and cons. RTG's and PV power systems have been extensively used in space, while SD and NRSPS are still in development. [Ref. 18: p. 2]

In a 1988 NASA report, Sovie [Ref. 18] states that using state-of-the-art technology for an initial lunar base would be cost-prohibitive. He asserts a state-of-the-art solar lunar base would require over 16,000 tonnes (16×10^6 kg) to LEO (mass to LEO = five x mass on lunar surface). Sovie therefore explains NASA's philosophy of utilizing advanced solar and and/or RTG systems for early missions and initial outposts. The stage will then be set for high-capacity nuclear power systems. In addition, the nuclear power plant will run electrolysis plants to provide economical H_2 and O_2 . Surface transportation would run on fuel cells. The savings in terms of mass to LEO, obtained by evolving to nuclear power instead of advanced solar systems are as follows:

- Manned outpost (100 kWe): 310,000 kg
- Interim base (9500 kWe): 1,746,500 kg
- Sustained base (2000 kWe): 7,225,000 kg [Ref. 18: p. 8]

Note that the development of advanced solar systems would provide a surface transportation option that could replace RTG's. [Ref. 18: pp. 7-8]

Independent calculations indicate that a state-of-the-art solar power plant on the Moon would require about 300 tonnes (3×10^5 kg) to LEO, based on the design of Appendix A. The reflector was assumed to be of light weight graphite epoxy materials which assure thermal stability and rigidity.

C. PHOTOVOLTAIC POWER SYSTEMS

Sovie [Ref. 18] states research on photovoltaic power systems is aimed at developing radiation tolerant, high-performance (> 20 percent efficiency), lightweight arrays (~300 $\frac{W}{kg}$), and increased capacity electrochemical storage systems. He cites major efforts in the development of indium phosphide (InP), amorphous silicon, and gallium arsenide (GaAs) solar cells, sodium/sulfur (NA/S) batteries, and H_2-O_2 regenerative fuel cells. InP cells have demonstrated efficiencies of 18.8% and are tolerant of radiation. GaAs concentrator arrays have efficiencies of 23.5% and have projected specific powers of 88 $\frac{W}{kg}$. Lower efficiency (approximately ten percent) amorphous silicon arrays have been developed and are extremely light-weight (six Watts per kilogram). Furthermore, these arrays are quite compact during launch. [Ref. 18: pp. 3-4]

Eventually, the technology for manufacturing solar cells from indigenous lunar material will be required for lunar base growth and expansion. Although the composition of the regolith is well-known at the Apollo sites, only theories exist to suggest possible solar cell production schemes. Much research is still required in this area. Only *in situ* experiments can demonstrate definitively the ability to manufacture solar cells for lunar base applications. [Ref. 17: p. 6]

D. ADVANCED SOLAR DYNAMIC SYSTEMS

Solar dynamic power systems offer great potential for efficient, light-weight, survivable, relatively compact, and long-lived power systems. The power levels obtainable range up to hundreds of kWe (kilowatt electric) or even megawatts. These systems are competitive with PV technologies in the very small sizes. However, solar dynamic systems become increasingly attractive for higher

power applications (over 50 kWe) where increased efficiency and compactness are required. Current efficiencies of 23% have been achieved experimentally in unconcentrated sunlight . The target minimum efficiency is 25 percent. [Ref. 18: p. 4]

Key objectives of the advanced solar dynamic program are to increase operating temperature and efficiency, while reducing weight of component elements. As with solar cell technology, much research remains toward practical lunar base applications. However, present plans to utilize advanced solar dynamic technology on the space station *Freedom* will provide operational experience from which to pursue a lunar base initiative. [Ref. 18: p. 4]

E. NUCLEAR POWER OPTIONS

Because the Moon experiences long diurnal cycles (the lunar night lasts 14 Earth-days), solar energy becomes an awkward energy source for a continuously inhabited and operated Moon settlement (except for polar locations). The constraining factor is the massive energy storage devices required for night-cycle operations. Buden and Angelo [Ref. 19] assert that nuclear energy offers a "relatively compact power source that is not affected by the diurnal day/night cycle, and the technology should be available if current development plans proceed as now scheduled." [Ref. 19: p. 91]

This sub-section will examine the possible applications of nuclear energy to lunar base applications and is divided into two topics. The first topic will list the advantages and disadvantages of radioisotope thermoelectric generators (RTG's). The second topic will depict various SP-100 system concepts applicable for lunar base utilization.

1. Radioisotope Thermoelectric Generators (RTG)

RTG's have been used where long life, high reliability, solar independence, and environmental tolerance is critical. These devices utilize the spontaneous decay of plutonium-238 as a source of heat. The energy is then converted to electricity by means of thermoelectrics placed next to the heat source. RTG's have been launched in at least 21 spacecraft. The first successful flight of a SNAP-3B power source was in 1961. An illustration of the longevity and reliability of RTG's can be seen in the *Pioneer* satellite, which after eleven years of operation, departed the solar system in a fully functional state. A more recent example is the *Voyager* spacecraft, whose spectacular photographs of the outer planets serve as testimonials to the performance of this type of power source. However, Buden and Angelo [Ref. 19] claim radioisotopes will not likely exceed 500 W. They do cite power levels of one to ten kilowatts possible from dynamic electric converters utilized in power conversion. [Ref. 19: pp. 91-92]

Burden and Angelo contend for initial lunar base applications, the SP-100 Program technology is applicable. Regolith can be utilized for radiation shielding while other elements of the system can be transported from Earth. The SP-100 Program, having been in existence since 1982, is a joint program of the Department of Energy, DARPA (Defense Advanced Research Projects Agency), and NASA to develop space nuclear power systems technology. The current program consists of three possible options and will be compared in the following sections. [Ref. 19: pp. 92-93]

2. SP-100 Program

The SP-100 system is defined by French [Ref. 20] as being a nuclear reactor-based electrical power plant designed for space use. Design performance

requirements specified for a 100 kWe system are presented in Table 19 [Ref. 20: p. 99]. The unit "rad" in Table 19 refers to the amount of radiation corresponding to 0.01 joule absorbed by one kilogram of material [Ref. 11: p. 103]. The initial lifetime goal is two years. However, French notes that no design characteristics exist which preclude a seven year interval of full power operation. [Ref. 20: pp. 99-100]

TABLE 19. SP-100 DESIGN PERFORMANCE REQUIREMENTS

Power	100 kWe
Mass	< 3000 kg
Launch Dimensions	STS bay diameter x 1/3 bay length
Radiation to Payload	500 K rad 7 yrs at full power

Radiation towards the payload is attenuated by a shadow shield that subtends a solid angle, generally in the 12°-17° half-angle range. The radiation levels are specified over a 4.5 diameter plane 25 meters from the opposite end of the reactor as illustrated in figure 5.2 [Ref. 19: p. 94]. The payload does not necessarily have to be 25 meters from the reactor. This dimension is merely a reference point for specifying radiation. The payload could be closer or farther than 25 meters as radiation requirements dictate. For uniformity, system designers researching the various concepts have all chosen to place the power conditioning and control subsystem at the 25 m point. Separation would be obtained by deploying an erectable boom structure after shuttle deployment but prior to reactor start-up. [Ref. 20: p. 100]

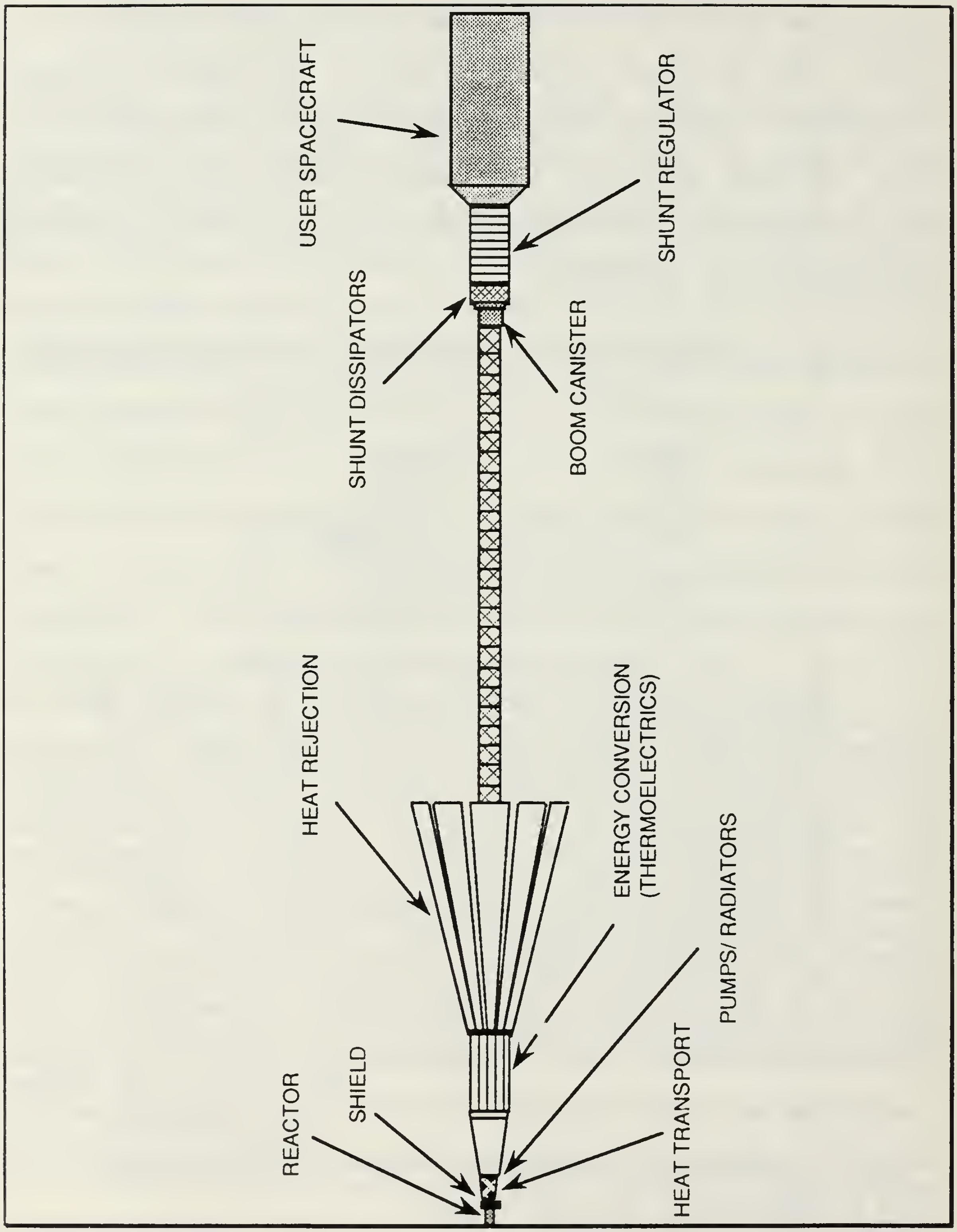


Figure 5.2 SP-100 Design

French [Ref. 20] presents three concepts presently being evaluated for possible selection. Table 20 [Ref. 20: p. 101] lists these concepts which are usually distinguished by reference to their means of conversion: thermoelectric, thermionic, and Stirling. [Ref. 20: p. 100]

TABLE 20. SP-100 SYSTEM CONCEPTS

Reactor	Heat Conversion	Heat Transfer	Rejection
Fast, compact	thermoelectric	pumped lithium	deployable heat pipe radiator
Fast, themionic	in-core thermionic	pumped NaK	fixed heat pipe radiator
Fast, compact	Stirling engine	pumped NaK	heat pipe or gas, probably deployable

a. Thermoelectric Concept

This concept is a derivative of the previously discussed RTG technology. The configuration of the thermoelectric concept results in a static system requiring no moving parts or thermal-to-electric conversion. However, materials constraints do limit the inlet and outlet temperatures. In addition, relatively low efficiency conversion results are obtained. The combination of these two factors require the deployment of a large waste-heat radiator. Nevertheless, the potentially high reliability and years of experience with RTG's are major explicit advantages of this system. The only "moving part" in the entire system is the lithium coolant which is electromagnetically pumped. This medium carries thermal energy through intermediate heat pipes to the hot side of the thermopiles. The radiator cools the cold side. [Ref. 20: p. 101]

b. Thermionic Concept

The thermionic configuration, pictured in Figure 5.3 [Ref. 19: p. 95], also contains no moving parts, unless the sodium-potassium (NaK) eutectic coolant is considered to be a moving element. Thermal-to-electric conversion occurs directly in the reactor with the nuclear fuel heating the thermionic emitters. The collectors are then cooled by the NaK coolant. The waste heat from the collectors directly goes to a heat exchanger and then the radiator. The radiator temperature and the conversion efficiency is higher than the thermoelectric case. Thus, a radiator smaller than the previous case can be utilized. French [Ref. 20] does note concern over possible life-limiting mechanisms in the thermionic converters. Inclusion of the conversion capability within the core results in larger and heavier reactors. This concern may be less significant at higher power levels. [Ref. 20: p. 101]

c. Stirling Concept

The Stirling system concept consists of a free-piston Stirling engine connected to a linear alternator with gas bearings, a liquid metal working fluid, and an electromagnetic pump. Considering all three concepts, this system offers the highest conversion efficiency. French [Ref. 20] cites a value of up to five times that of the thermoelectric system. However, this technology is less developed than the static concepts. Nonetheless, the prospect of lower operating reactor temperatures and higher performance makes this system noteworthy. Areas of concern involve the dynamic nature of the system and therefore the resulting potential for wear and vibration. Another area requiring attention is the efficient means of heat input and withdrawal to and from the multiple engines. [Ref. 20: p. 101]

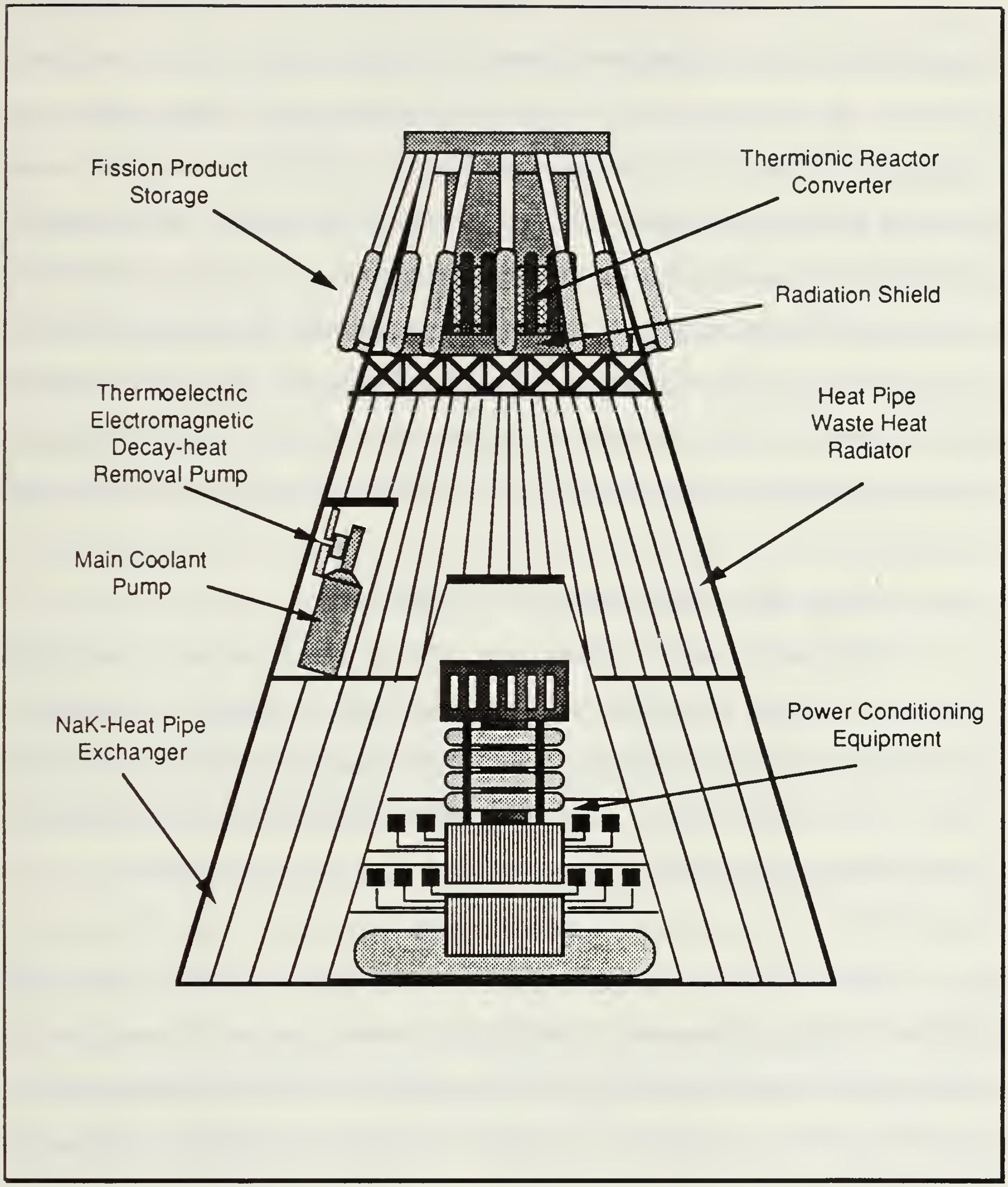


Figure 5.3 Thermionic Power Plant Concept

For a variety of reasons, French [Ref. 20] states that SP-100 design configurations under development cannot be directly applied to a Moon base. However, the technology and components resulting from the program can certainly be utilized for lunar base employment. Problems which arise are generally due to the presence of the lunar surface. The current configuration of the SP-100 is designed for space use; no material is in the vicinity except for the system itself and the user spacecraft. Because radiation can be scattered back toward the reactor by surrounding material, the presence of the lunar surface could cause very small changes in critical mass for given control settings. However, this effect should be within the control capability of the SP-100. [Ref. 20: p. 102]

3. Lunar Base Applications of the SP-100

The presence of the lunar surface will tend to diminish the effect of the waste heat radiator due to the reduced view factor to space. The problem becomes severe during the lunar day when the surface itself becomes a heat source in the infrared range. As a result, a larger radiator surface is required. This problem of heat dissipation becomes less intense at higher latitudes. [Ref. 20: p. 102]

The lunar environment, however, can be useful in other ways. The shadowed shield in the present design only protects a very small area. Such a configuration would be unsuitable for manned lunar surface applications unless the power plant was situated at a considerable distance from the base. The use of lunar soil or rock has been suggested as a possible solution to this problem. Although not especially efficient, regolith is freely available and is more appealing than the prospect of transporting 20,000-30,000 kg of more efficient

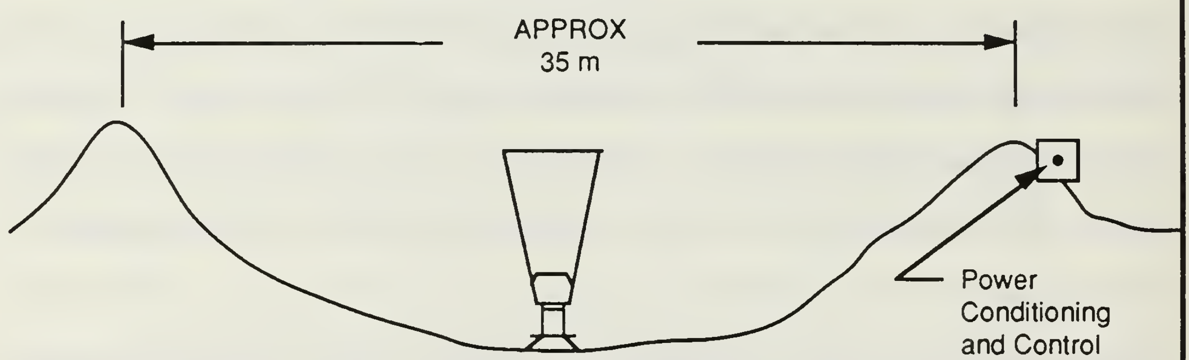
material from Earth. Two approaches for shielding are available: placing the reactor in the bottom of a convenient crater or building up a structure around the reactor. [Ref. 20: pp. 102-103]

Figure 5.4 [Ref. 20: p. 103] illustrates the crater concept. Although the simpler of the two approaches, there may be some inherent problems associated with this concept. For example, in order to provide the necessary depth, the crater dimensions would accordingly be large. The entire reactor system would reside in the crater to minimize plumbing lengths for liquid metal. Once the reactor becomes operational, the interior of the crater and therefore, the entire system must remain off-limits. After extensive operations, the accumulation of fission products would prevent close approach even with the reactor shut down. Although the reactor will be designed for unattended operation, periodic manned inspection and maintenance will be required. An additional problem for electronic equipment is the reflected radiation from the surface. The power conditioning and control unit would have to be placed beyond the crater or else be adequately shielded. [Ref. 20: p. 103]

Further examination of Figure 5.4 suggest the shielding configuration worsens the heat rejection problem by further degrading the view of space. Figure 5.5 [Ref. 20: p. 103] depicts conceptually how an SP-100 system might be adapted to function more efficiently in a crater environment. Note, the thermoelectric concept may require a shadow shield to protect the thermoelectric converters. [Ref. 20: p. 104]

A reconfigured SP-100 system combined with a custom built shield is illustrated in Figure 5.6 [Ref. 20: p. 104]. Slightly different configurations are shown for the various conversion concepts. The conversion systems can be

shielded from the reactor, but the trade-off is in increased liquid metal plumbing runs. The advantage of maintenance and replacement, however, becomes attainable. Similar shielding trade-offs apply to the radiator. [Ref. 20: p. 104]



A generic space-type SP-100 mounted in a crater for shielding as often suggested is depicted. Based upon scaling the geometry of the Barringer crater in Arizona, a 6.1 m long SP-100 would require an approximate 35 m diameter crater. (Note : Because of scattering, even the radiator must be shielded from manned presence. Thus, unless a large quarantine area is specifie , the crater must encompass the complete system.) A longer SP-100, i.e., deployable radiator, would require a still larger crater. Since most heat is rejected from the outside of the cone, the radiator view factor is poor.

Figure 5.4 SP-100 Crater Concept

As mentioned earlier, the preferred concept of the two approaches is not certain. Although the shielding process requires more preparation than the crater approach, French [Ref. 20] considers the possibility of the two concepts being two evolutionary stages. He further states that the likelihood of such an evolution seems probable since more than one power plant will ultimately be required for the base. [Ref. 20: pp. 104-105]

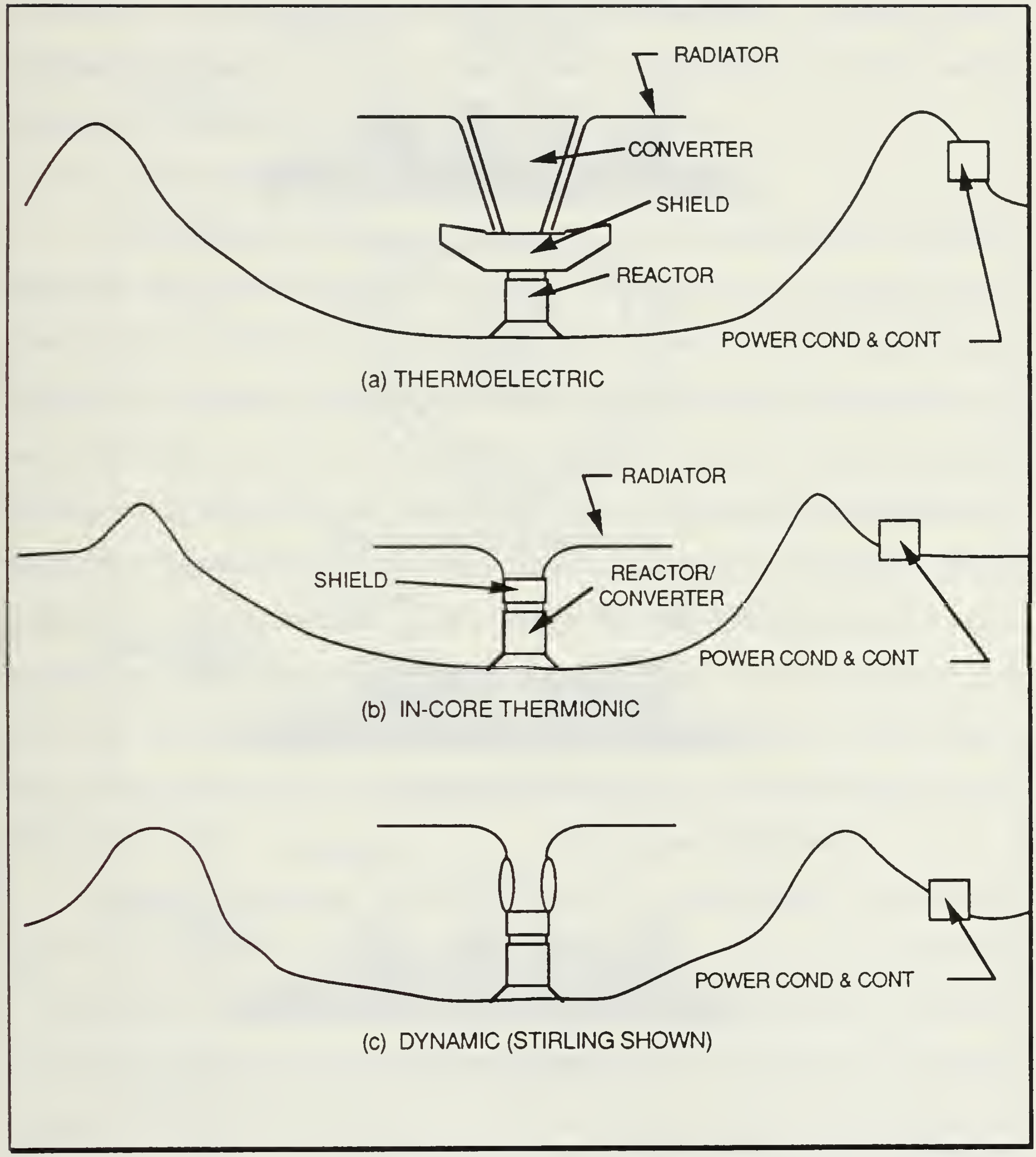


Figure 5.5 Possible Reconfigurations of the SP-100

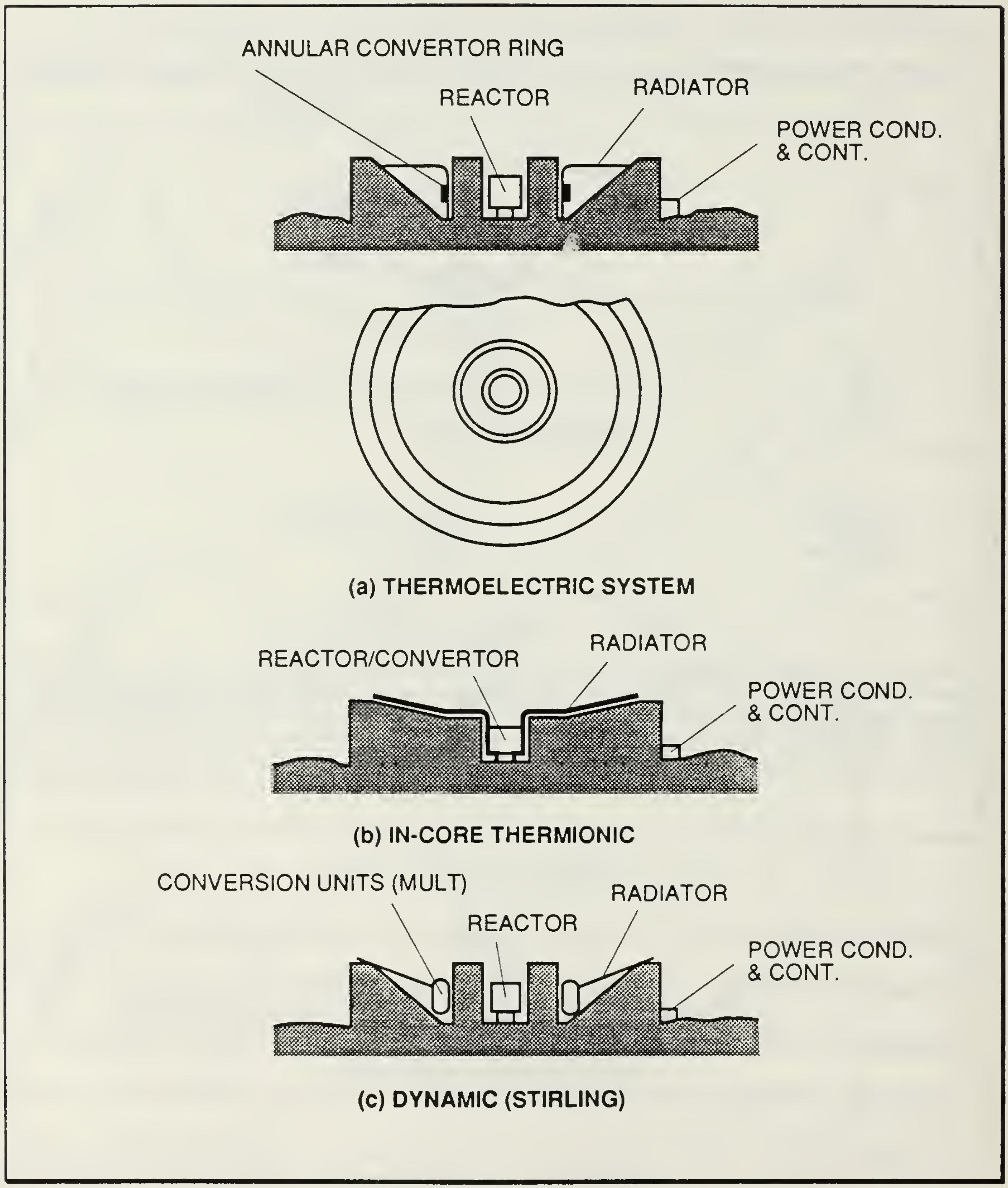


Figure 5.6 SP-100 Shielding Concepts

The changes outlined for the adaptation of the space-based SP-100 to the Moon's surface have encompassed either a simple reconfiguration of major components or relatively minor changes in the components. A completely new development program parallel to the present SP-100 initiative will not be necessary to provide lunar base power. [Ref. 20: p. 105]

4. Operational Considerations

An important advantage of nuclear power is the capability to operate during the entire lunar diurnal cycle. Except for polar sites, a solar-based power system requires additional measures to cope with the two week day/night periods. Specifically, a massive power storage system would be needed during the night period (except for polar sites). Another alternative is to reduce the power requirement by eliminating all loads except vital systems during night operations. But even a "powered-down" lunar base would still necessitate substantial power generation. The advantage of solar arrays situated at high-elevation polar regions has been previously discussed in Chapter III. However, the selection of a polar site will influence other factors of lunar base operations. On the other hand, nuclear power does not constrain the selection of the Moon base location. [Ref. 20: p. 105]

Another advantage of nuclear power is the residual "waste heat" generated through the conversion process. In the spacecraft version, the SP-100 "waste heat" is radiated to space. The lunar applications illustrated in Figures 5.5 and 5.6 illustrate a similar configuration in that the waste heat is also radiated to space. However, the design can easily be altered to utilize "waste heat" for direct applications such as base heating or materials processing. Thus, the overall requirement for electrical energy would be reduced. [Ref. 20: p. 105]

5. Growth Potential

One other application of the excess heat could be the generation of additional electrical energy. Supplementary conversion units could be coupled with the primary unit to accept excess heat. Of the three concepts previously discussed, the in-core thermionic primary system is potentially the best configuration for utilization of waste heat. The reason is because the in-core arrangement generates the highest temperature of the three potential concepts. The coupling of one or several Stirling units to the system would represent a "bottoming cycle." The highly efficient Stirling units operate at inlet temperatures compatible with the 1000 K heat rejection temperature of the primary thermionic system. [Ref. 20: pp. 105-106]

Similar coupling configurations can be derived utilizing a thermoelectric unit. However, the rejection temperature is lower than the thermionic case. Waste heat is still available from the resulting combination of units, but at a considerably lower temperature of 500-700 K. The major advantage of the "bottoming cycle" approach is the potential for phased development. With the proper design, converters can be added to an already established and functional power system. Thus, potential growth is incorporated into system design without requiring the installation of a new reactor. [Ref. 20: p. 106]

F. POSSIBLE ROLE OF SUPERCONDUCTIVITY

The recent development of superconducting ceramics have introduced an entirely new dimension in the search for feasible lunar base power. The possibility of manufacturing superconducting ceramics from lunar rocks and providing the necessary cooling through natural means is discussed in a 1987

article by Lawton and Wright [Ref. 21]. This section will present their ideas on lunar base applications of superconducting technology.

1. Superconductivity Background

Materials exhibiting superconducting characteristics have been known for nearly a century. However, these materials required temperatures close to Absolute Zero and were continuously immersed in liquid helium (temperature 4.3 K). Other specialized alloys based largely on niobium, tin, zirconium and trace metals were capable of exhibiting superconductivity at a higher temperature of 20.4 K, the temperature of liquid hydrogen. The storage of liquid hydrogen is easier in the lunar environment than on Earth. In view of past geological surveys, the prospect of discovering hydrogen in the form of hydrides in lunar rocks or as frozen water is not promising. Therefore, Lawton and Wright [Ref. 21] explain the exploitation of superconductivity was not practical for lunar applications until the discovery of superconducting ceramics in 1987. [Ref. 21: p. 359]

Superconducting ceramics exhibit superconducting properties at much higher temperatures than previously possible. Thus, these materials can perform at the temperature of liquid nitrogen, 77 K. Recent developments have even permitted the use of liquid oxygen at 90 K as the cooling medium. As previously discussed in Chapter III, the production of lunar oxygen is an attainable goal for a lunar base. The major technological problem may be how to fabricate long transmission lines (kilometers) out of ceramics. [Ref. 21: p. 359]

2. Lunar Applications

Inevitably, electrical power will be required at sites considerably distant from the location of the power plant. An example might be a mining operation

several hundreds of kilometers away from the lunar base. Electricity will be required to process ores. Lawton and Wright [Ref. 21] list several examples of metals produced by electrolysis: aluminum, titanium, and magnesium--all found in lunar rocks. Locally generated electricity may not be possible, and the use of copper or aluminum cables will result in considerable losses. The use of superconducting cables may avoid such problems. In addition, Lawton and Wright assert that careful planning of the cable layout could result in a naturally cooled configuration. Furthermore, the cable could be made from Moon rocks and materials. Table 21 [Ref. 21: p. 360] lists the required basic elements. Gold has been successfully utilized to bind the superconducting ceramic crystals into a matrix which permits the material to be drawn into ribbon, tape, or wire without affecting the superconducting properties of the basic material. [Ref. 21: pp. 359-360]

TABLE 21. SUPERCONDUCTING ELEMENTS

Element	Amount Required
europium	trace elements only
yttrium	trace element only
lanthanum	trace element only
barium	fraction element
copper	bulk element
gold	fraction element
oxygen	bulk element

3. Lunar Cooling

During the lunar day, the surface of the Moon reaches a temperature of 400 K (130°C) at the equator. Apollo *in situ* measurements gave a minimum subsurface temperature of 250 K. During the lunar night, the temperature drops

to approximately 73 K (-200°C). Lawton and Wright [Ref. 21] hypothesize an area not receiving direct sunlight will permanently remain at 73 K, well below the 273 K freezing point of water. They further imply ceramic superconducting cables or conductors can be housed in deep "troughs" or trenches constructed to keep the cables permanently in shadow. The cables will then be subjected to approximately the same temperature as the sloping sides of the though which radiates to space. Lawton and Wright maintain that a stable temperature between 80 K and 90 K is obtainable by a sufficiently deep trough and sunless exposure. [Ref. 21: p. 360]

Regolith has a low bulk density ranging from 1.5 to 1.6 $\frac{gm}{cm^3}$ but the individual grain density is 3.1 to 3.5 $\frac{gm}{cm^3}$. Therefore, half the volume of the lunar surface is empty space and regolith, and as such, serves as an excellent heat insulator. Optimistically, Lawton and Wright [Ref. 21] state regolith may serve as a good electrical insulator, in which case their proposed power transmission lines would consist of a pair of uninsulated superconductor cables in two parallel deep trenches, side-by-side in the sunless regolith. [Ref. 21: p. 360]

4. Electromagnetic Launchers

A possible solution for transporting minerals and metals processed from the Moon is the use of electromagnetic launchers. Current proposals envision materials being launched from the surface of the Moon to the L_5 Lagrange position or some other suitable orbital location. Since the lunar gravity is one-sixth of Earth's gravity, the escape velocity is considerably less. Furthermore, recent research indicates the latest superconducting material can withstand intense magnetic fields. If suitable lunar rock superconductors are discovered, an electromagnetic launcher could be set up very cheaply. [Ref. 21: p. 361]

Lawton and Wright [Ref. 21] suggest the launchers could be operated during the lunar night. Electrical power would be derived from solar panels situated on the sunlit side of Moon, supplied by the loss-less superconducting power grid. All the materials would be indigenous to the Moon, with little or few materials transported from Earth. [Ref. 21: p. 361]

5. Magnetic Levitation Railway

A superconductor will not permit a magnetic field to pass through it. A considerable repulsive force is generated and results in the levitation of the superconducting material. If the material is attached to a carrier, it is also levitated as well as the payload. An alternating component to the magnetic field could provide a propulsive force. [Ref. 21: p. 361]

Superconducting magnetic levitation is a common demonstration, and is in fact a standard test of superconductivity. Thus far, railway applications have been limited to research studies. The major hurdle is associated with liquid hydrogen cooling of magnets wound from niobium tin wire. Unlike the Earth, the reduced lunar gravitational field would allow greater loads to be lifted. In addition, the problem of cooling would be reduced. Adopting a completely integrated approach could result in a totally superconducting power distribution system, in combination with a rail transportation system and electromagnetic launchers. [Ref. 21: p. 361]

This chapter has examined the question of lunar base power. Advanced power systems were compared, photovoltaic and advanced solar dynamic systems were examined. Nuclear power options were contrasted to solar power alternatives. Specific system concepts of the SP-100 program were presented and illustrated. Next, lunar applications of modified SP-100 configurations were

contrasted. In addition, system operational and growth considerations were discussed. Finally, a brief overview of current superconductivity technology and lunar applicability was conducted. The possibility of natural lunar cooling, electromagnetic launchers, and magnetic levitation railways were addressed. The next chapter will discuss transportation issues related to establishing a lunar base.

VI. TRANSPORTATION

This chapter will examine transportation issues related to a lunar base endeavor. Section A will define options for mission architecture and infrastructure support required for establishing and maintaining a Moon base. Section B will present a brief overview of flight mechanics and related lunar orbital parameters. Mission modes will be specified in Section C. Finally, transportation costs and logistical conclusions will be discussed in Sections D and E respectively.

A. INFRASTRUCTURE

This section is divided into two parts. The first sub-section will list possible options for mission architecture. The second sub-section will compare infrastructure considerations for lunar support.

1. Mission Architecture

The establishment of a lunar base will be driven by mission strategy, as previously illustrated in Chapter III. Additionally, architectural and system engineering trade-offs will also impact the lunar base design. Current studies examine questions relating to the requirement for artificial Earth gravity (1 g) versus the reduced lunar gravity ($\frac{1}{6}g$), the use of transportation nodes, the integration of launch vehicles and spacecraft, and new forms of propulsion, such as a solar sail [Ref. 22: p. 36].

Another driving force in architecture is the choice between temporary expeditions and an evolutionary strategy described in Chapter III. Temporary expeditions keep up-front investments to a minimum, but long term costs are

greater than the evolutionary missions. An example of a worst-case scenario is the Apollo program, in which lack of commitment to a long-term plan resulted in the development of single-use, "dead end" hardware vice evolutionary, long-term equipment. Therefore, the concept described in previous chapters, utilizing equipment brought by previous missions to augment future expeditions, is presently under consideration as part of a long-range master plan. [Ref. 22: p. 37]

In a 1989 article on lunar program architecture, Bekey [Ref. 22] states a major investment in infrastructure will be essential. However, he notes the open question regarding which infrastructure is best: one that assembles spacecraft in LEO from numerous components launched by heavy lift vehicles, or a predominantly ground-based infrastructure capable of developing a booster large enough to launch an entire spacecraft in one or several components? Perhaps the deciding factor could be the increasing hazard posed by space debris in LEO. [Ref. 22: p. 37]

Bekey [Ref 22] further asserts many plans for lunar missions utilize "transportation way points or nodes for assembly, staging, docking as well as for checkout and fueling." [Ref. 22: p. 38] However, he states the location of such nodes is unclear. One probable location is in low Earth orbit, but should another node exist in lunar orbit, at a libration point, or in a permanently circulating trajectory? Again, these decisions will impact mission architecture and infrastructure design. [Ref 22: p. 38]

2. Infrastructure Considerations

Support elements necessary for manned exploration include Earth-to-orbit launch vehicles, Earth orbiting facilities such as the space station *Freedom*,

and transportation nodes in orbit around the Moon. All human-exploration missions will deliver substantial payloads to LEO; Moon base estimates are in the vicinity of 100 metric tons. There is an obvious need to augment current launch capabilities, since the Titan IV and Space Shuttle can only deliver 18 metric tons to the 220-nm orbit planned for *Freedom*. Lovelace *et al.* [Ref. 23] state that a vehicle with a 90-100 metric ton capability to LEO is a requirement for manned exploration. In addition, they propose a capacity of 140-175 metric tons per launch would further simplify the mission. [Ref. 23: p. 39]

For exploration missions, the Space Shuttle appears to be adequate for crew delivery to low Earth orbit. However, cargo requirements may necessitate another launch vehicle capable of delivering an annual payload capacity of 500-1000 metric tons. As a preliminary tep, NASA is developing Shuttle-C, a cargo version derived from shuttle design, capable of placing 50-75 metric tons in space station orbit. In a 1989 article on lunar infrastructure considerations, Lovelace *et al.* [Ref. 23] state "flights could begin in as few as four years from approval to meet lunar launch requirements." [Ref. 23: p. 39]

As an entirely new development structured toward simpler operations, increased launch rates, and lower recurring launch costs, the Air Force and NASA are defining the concept of the advanced launch system (ALS). Payload weights of as much as 91 metric tons (200,000 lbs) are expected to be delivered to LEO. Also under consideration are vehicles composed of multiple shuttle main engines and advanced solid rocket motor components configured around larger diameter fuel tanks. A capability of 250-260 metric tons per launch is projected. Such vehicles could be utilized for lunar missions as well as Mars missions. [Ref. 23: p. 39]

Infrastructure in Earth orbit required for human exploration support includes an orbital facility for "assembly and servicing of vehicles, crew transfer, refueling, life sciences research, and technology demonstrations." [Ref. 23: p. 39] Various options exist for utilizing the space station. For example, one viable option for meeting all support needs is the upgrade of the original facility in orbit. Another alternative is the construction of a completely separate facility in LEO. Variations of these two options include the division of functions between the space station and a "free flying facility." Lovelace *et al.* [Ref. 23] cite another alternative: "the assembly and fueling of vehicles in a self-sufficient mode some distance from *Freedom*, while depending on the station for precursor research, technology development and demonstration, and operational support such as checkout and repair." [Ref. 23: p. 39] This option would require less growth of the space station and retain the multi-use capability. [Ref. 23: p. 39]

On-orbit vehicle processing shares many of the same functions as orbital assembly. Tasks such as handling, mating, and manipulating large masses are examples of these functions. Additionally, the integration and testing of the entire space vehicle must be accomplished. Accomplishing such complex tasks in orbit, where previously always accomplished on the ground, requires new procedures, advance equipment (such as the Orbital Maneuvering Vehicle being developed by TRW), and an entirely new operational philosophy. Furthermore, the exposure time in LEO to space debris is a major concern. [Ref. 23: p. 40]

The establishment of a lunar base requires a substantial support infrastructure. One possible configuration is illustrated in Figure 6.1 [Ref. 3: p. 139]. The numbers from Figure 6.1 represent the following evolutions:

1. The crew bound for the Moon travels from the Earth's surface to the Earth spaceport in a passenger transport vehicle.
2. At the Earth spaceport they board a transfer vehicle to take them to the lunar spaceport.
3. At the lunar spaceport, they board a lunar lander to take them to the surface of the Moon.
4. On its return to Earth, the transfer vehicle is aerobraked in Earth's atmosphere prior to its rendezvous with the Earth spaceport. [Ref. 3: p. 139]

Prior to placing these facilities in space, existing technology must be augmented and adequately tested. Mission areas required for demonstration of advanced technology to support infrastructure requirements include: power and thermal systems, servicing techniques, waste treatment, communications, space debris control and use of libration points. [Ref. 9: p. 6]

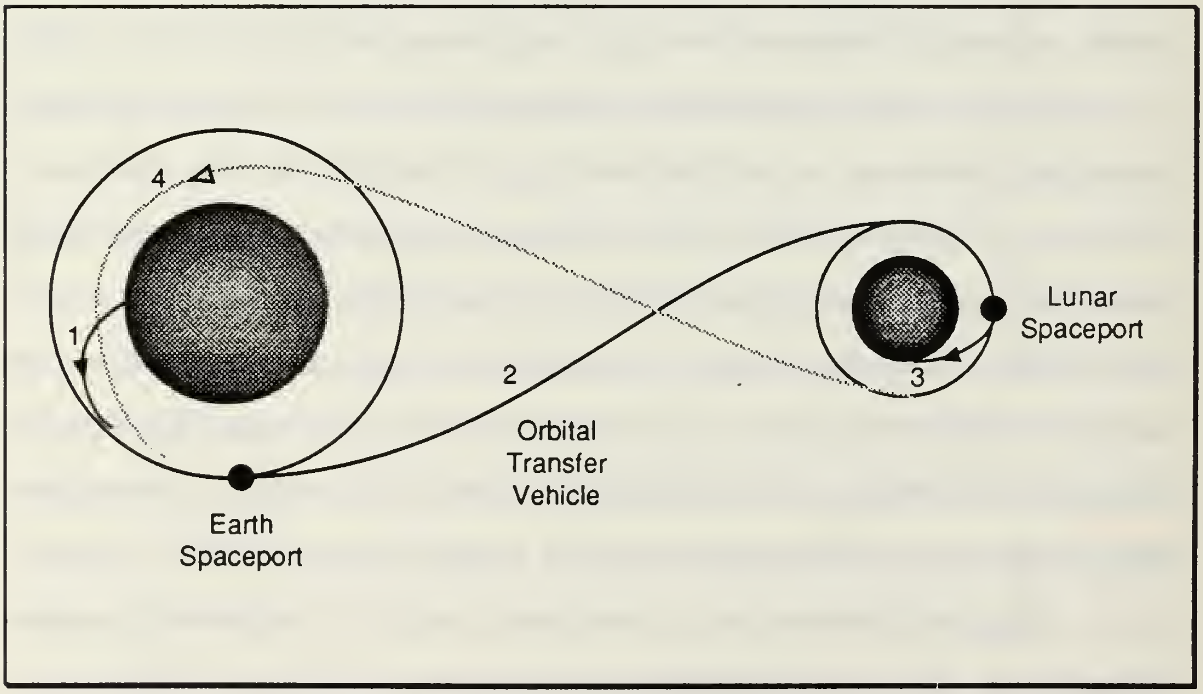


Figure 6.1 From Earth to Moon

B. FLIGHT MECHANICS

This sub-section will give a brief introduction to Earth-Moon flight mechanics needed as background for the remaining sections. It is divided into four parts: Section 1 defines lunar orbital parameters, Section 2 explains lunar librations, Section 3 introduces the Lagrange points, and Section 4 evaluates space station-lunar dynamics.

1. Orbital Parameters

The notion that the Moon revolves about the Earth is somewhat misleading. A more precise description is that both the Earth and the Moon revolve around a common center of mass. The mean distance between the center of Earth and the center of the Moon is 384,400 kilometers. The mass of the Moon is $\frac{1}{81.30}$ of the mass of Earth. The center of the system is 4,671 kilometers from the center of the Earth. [Ref. 24: p. 323]

The description of the motion of the Earth-Moon system is complex. First, the center of mass revolves around the Sun once per year. Next, the Earth and Moon revolve about their common center of mass once every 27.3 days. As a result, the longitude of objects such as the Sun or nearby planets exhibit fluctuations with a period of 27.3 days. This is because observations are made from the Earth and not from the system center of mass. Finally, the orbital period of the Moon is not constant. Rather, it is slowly increasing at the same time the Earth-Moon distance is increasing. [Ref. 24: p. 323]

The Moon's orbit can be described by six classical orbital elements when viewed from the center of the Earth:

- a--semi-major axis
- e--eccentricity

- i--inclination
- Ω--longitude of the ascending node
- ω--argument of perigee
- α--right ascension at epoch

These orbital elements are illustrated in figure 6.2 [Ref. 24: p. 324]. The Moon's orbital elements are constantly changing with time, primarily due to the perturbational effects of the Sun. [Ref. 24: pp. 324-325]

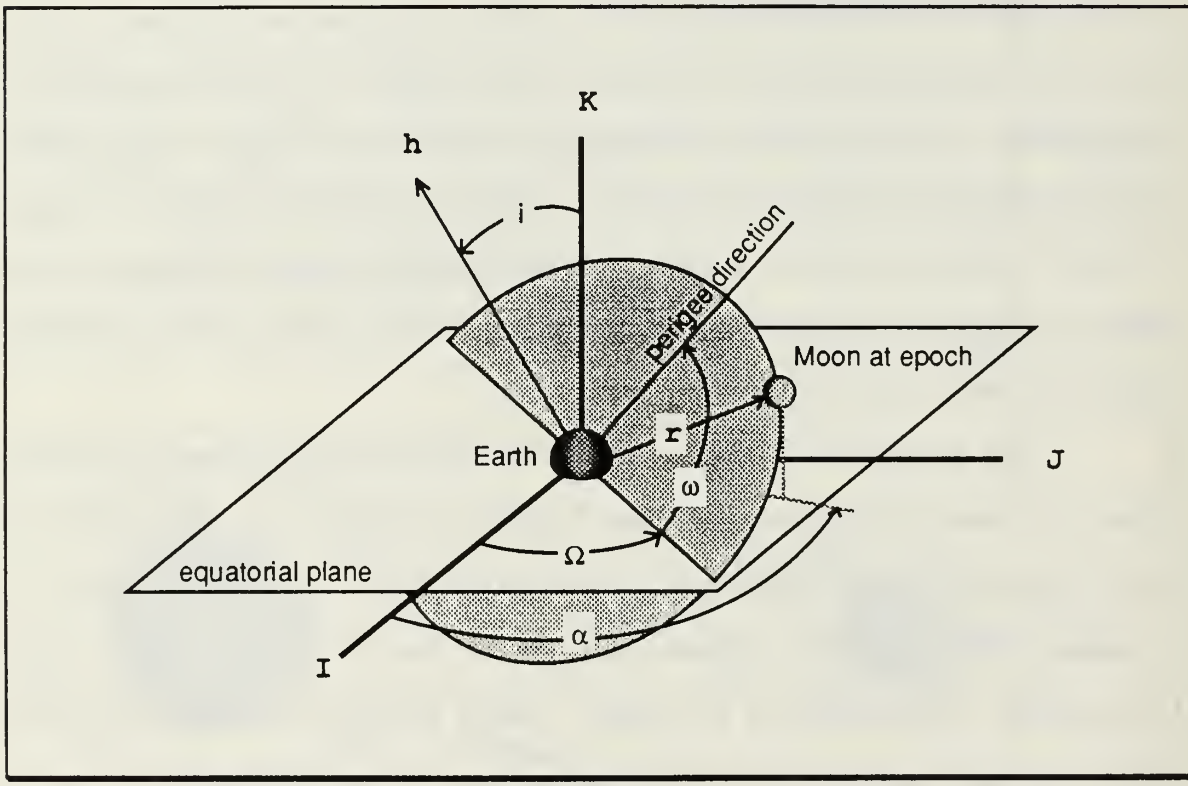


Figure 6.2 Lunar Orbital Elements

a. Semi-major Axis

The mean value of the semi-major axis is 384,400 km. The average time for the Moon to complete one revolution around the Earth is 27.31661 days. Solar perturbations cause variations of the sidereal period amounting for as much as seven hours. [Ref. 24: p. 325]

b. Eccentricity

The mean eccentricity of the Moon's orbit is 0.054900489. At intervals of 31.8 days, small periodic changes of orbital eccentricity occur. This effect is called "evection." [Ref. 24: p. 325]

c. Inclination and Line of Nodes

The Moon's orbital plane is inclined to the ecliptic (the Earth's orbital plane) approximately 5°8'. The line of nodes is the intersection of the two orbital planes, and rotates westward. One complete revolution of the line of nodes occurs every 18.6 years. The node where the Moon crosses the ecliptic from south to north is known as the ascending node. The opposite node, where the Moon crosses from north to south is called the descending node. Eclipses occur at these nodal points, since only at these locations are the Sun, Earth, and Moon properly aligned. The average time interval between node to (the same) node crossing is 27.21222 days and is referred to as the "draconian period." [Ref. 24: p. 326]

d. Line of Apsides

The line of apsides is defined by the line joining perigee and apogee. Apsidal rotation occurs in the direction of the Moon's orbital motion. As a result, ω changes 360° in approximately 8.9 years. [Ref. 24: p. 326]

2. Lunar Librations

The Moon always keeps the same face towards the Earth because the period of revolution around the Earth is equal to the period of rotation on its axis. If the Moon's orbit were perfectly circular ($e = 0$) and if the axis of rotation were perpendicular to its orbit, we would observe exactly half the lunar surface. [Ref. 24: pp. 326-327]

Actually, the Moon presents about 59 percent of the lunar surface because of a phenomena known as "lunar libration." The libration or "rocking motion" of the Moon can be attributed to two causes. The geometrical libration in latitude occurs because the Moon's equator is inclined 6.5° from its orbital plane. Once each month, the Moon's north pole is canted towards the Earth. Two weeks later, the south pole becomes tipped towards Earth. Therefore, observation beyond each lunar pole is possible from Earth. [Ref. 24: p. 327]

The geometrical libration in longitude is caused by the eccentricity of the Moon's orbit. The rotation of the Moon on its axis is uniform, but its angular velocity about its orbit is not. Recall Keppler's Laws of orbital motion. The Moon is moving faster at perigee than at apogee. As a result, 7.75° around each limb is visible from Earth. [Ref. 24: p. 327]

In addition to the apparent rocking motion described above, an actual rocking called "physical libration" is caused by "the attraction of the Earth along the diameter of the Moon's triaxial ellipsoid figure." [Ref. 24: p. 327]

3. Lagrange Points

There exist five points in the Earth-Moon system where space stations can remain without significant expenditures of energy. These points are known as Lagrange points.and are numbered from L_1 through L_5. Figure 6.3 [Ref. 3: p. 132] illustrates the relative positions of the Lagrange points. L_1 through L_3 are colinear because they are located along the Earth-Moon line. In addition, these colinear points are considered unstable: small perturbations will cause a drift without limit from its initial position. L_4 and L_5, on the other hand, form the apex of an equilateral triangle between the Earth and the Moon. These points are considered stable because a space station will remain within a certain

bounded distance when perturbed by small forces such as solar gravity. [Ref. 3: pp. 131-132]

Lagrange points appear to be promising for a variety of reasons:

- there is no atmosphere to limit astronomical and astrophysical observations
- the lack of magnetic fields or radiation belts
- continuous observations of objects in space is possible in any direction
- theoreticaliy, no power is required to maintain stationary orbits at L_4 and L_5
- communications will be greatly enhanced because with the exception of L_2, all points are visible from Earth [Ref. 25: pp. 59-60]

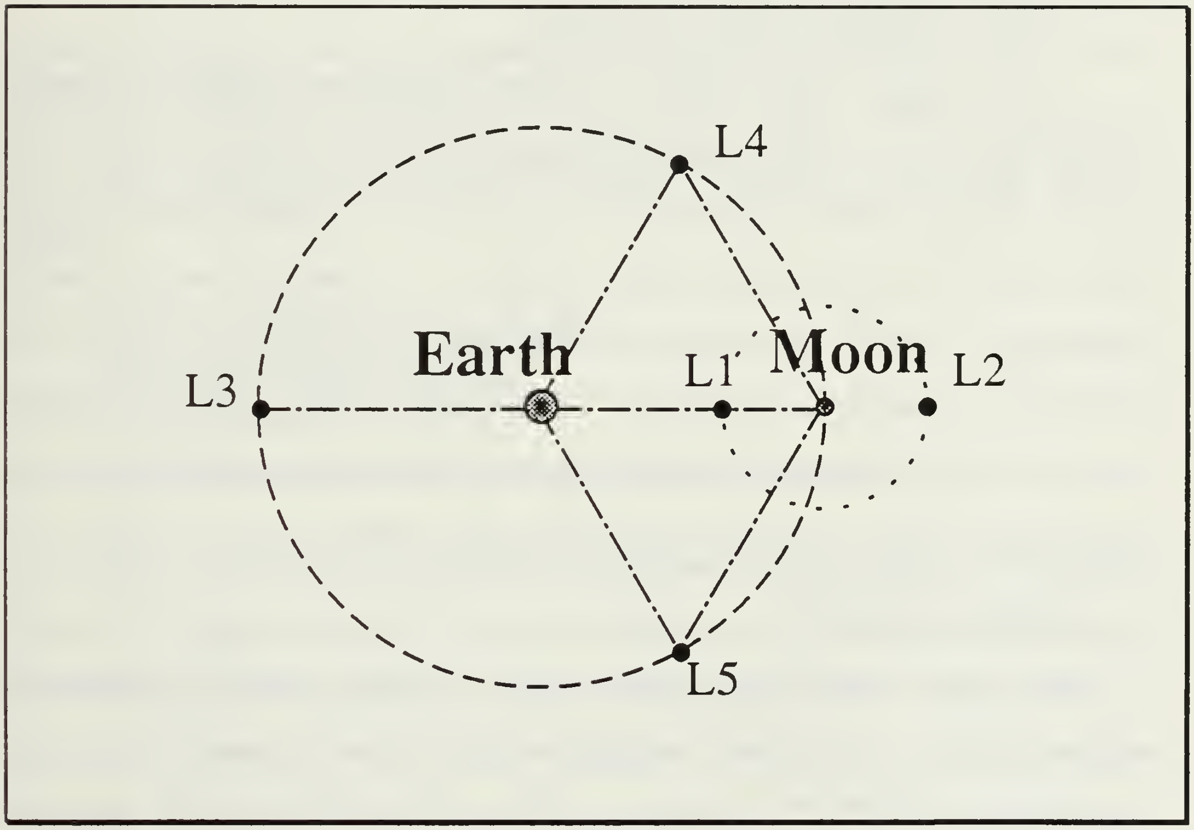


Figure 6.3 Libration Points in the Earth-Moon System

Due to their relative proximity to the Moon, L_1 and L_2 are the most likely candidates for a spaceport. Of course, L_1 has the added advantage of being visible from Earth. Other viable alternatives for a spaceport include circular orbits in the Earth-Moon system, highly elliptical orbits similar to the Soviet Molniya orbit, and cycling trajectories. The latter orbits and trajectories transit near the Earth and Moon as they loop around these bodies. Spacecraft would receive gravitational assists similar to a sling-shot effect with each passage near the Earth or Moon., and therefor maintain the same relative position during the Moon's 28-day cycle about the Earth. [Ref. 3: p. 132]

4. Space Station-Lunar Dynamics

NASA plans to place the space station *Freedom* in an orbital inclination of 28.5° (minimum energy orbit for Cape Canaveral launches). Given this figure exceeds the Moon's maximum inclination (5.1°), in-plane orbital transfers from *Freedom* to the Moon are always possible. The minimum energy transfer requirement is that the vector from Earth to Moon (at the time of arrival) must lie in the space station's orbital plane. The frequency of this occurrence depends on the orbit of the Moon and the space station. On the average, the Moon passes through the station's orbital plane every nine days. [Ref. 26: pp. 112-113]

C. MISSION MODES

This section is divided into three portions. The first sub-section will define trajectory options. The second sub-section will compare alternatives for lunar transportation. Finally, the third sub-section will list the elements of a possible transportation system.

1. Trajectory

There are two mission modes for access to the lunar surface from low Earth orbit:

- direct flight to surface
- orbital rendezvous

Perturbations discussed earlier must be accounted in any trajectory calculations. Though non-trivial, the direct flight trajectory is less complex and far less constrained than orbital rendezvous schemes. [Ref. 2: p. 4]

In a 1985 report on lunar and planetary mission impact on the space station, Woodcock [Ref. 2] completed an in depth study of lunar base logistics. In this report, Woodcock proposes various modes of final orbital configurations. The orbital rendezvous alternatives proposed include the following types of orbits:

- lunar equatorial (low inclination)
- lunar polar (high inclination)
- "halo" orbit about L_1 or L_2
- swing orbit (circulates between Earth and the Moon)

If no timing constraints are specified, a minimum-energy transfer orbit window, from a low Earth orbit space station (at inclination 28.5° and altitude 500 km) to the Moon, is available every nine days. Direct flights to the lunar surface and halo orbits encompass no timing constraints. The equatorial lunar orbit will have no timing constraints only if a Δv penalty of 75 $\frac{m}{s}$ is acceptable upon entering and departing lunar orbit. Equatorial and polar orbits have penalty-free opportunities once every 55 days (two lunar sidereal months). The out-of-plane

Δv penalty for the polar option is quite high and therefore, this type of orbit is constrained to the 55 day window. [Ref. 2: p. 4]

The polar option, if repeatedly utilized, requires the synchronization of space station nodal regression with the lunar sidereal month. Thus, an additional constraint is placed on the space station. With the exception of the equatorial orbit, all of Woodcock's orbits permit access to any point on the lunar surface. The requirement to land at a particular site obviously further complicates timing constraints. Figure 6.4 [Ref. 2: p. 5] is a summary of lunar mission modes. [Ref. 2: p. 4]

2. Lunar Transportation Considerations

The preferred flight profile for transportation to the Moon is similar to the Apollo mission mode. These missions were characterized by staging areas in lunar orbit. A manned lunar station could serve as a traffic node. Refueling and maintenance operations, as well as rescue operations would be conducted at such a station. Lunar cargo flights would go directly from the Earth's surface to the Moon. Bypassing the space station results in operational simplicity, flexibility, and minimizes costs. [Ref. 5: p. 477]

Passenger flight missions differ from cargo missions. After initial launch, passengers rendezvous with the Earth space station. Next, passengers board an orbital transfer vehicle (OTV). This OTV will eventually fly to a lunar orbiting station. Aerobraking in the Earth's atmosphere, the same OTV is utilized for the return-flight and rendezvous with the space station. A lunar lander will be required to transport personnel from lunar orbit to the surface of the Moon. The design of this lander is similar to the OTV, except the aerobrake is exchanged for landing legs. Multi-engine design will be a requirement for

safety considerations. Total flight time will be in the range of 60 to 80 hours. [Ref. 5: pp. 477-478]

Parameter	Lunar Staging Point			
	Lunar equatorial orbit (100 km)	Lunar polar orbit (100 km)	Earth-Moon L2 halo orbit	Lunar surface
Lunar surface site access	Near Lunar equator only	Any	Any	Any
Transit time, Earth-staging point	3-5 days	3-5 days	5-8 days	3-5 days
Wait at staging point	Not required	14-28 days (usually 14)	Up to 7 days for lowest ΔV	Not required
Transit time staging point-lunar surface	About 2 hours	About 2 hours	3 days	Not applicable
Departure window frequency, space station orbit	About 9 days	55 days	About 9 days	About 9 days
Access by mass driver	Once/orbit	Window 14 days	Window 15 days	Not applicable
ΔV m/s Earth-staging point Staging point-surface Staging point-Earth	 4010 2100/2000 1110	 4010 2100/2000 1110	 3375 2950/2850 435	 6110 Not applicable 3110

Figure 6.4 Summary of Lunar Mission Modes

As determined by Woodcock, a launch window occurs every nine days for minimum energy trajectories. However, such a limitation is not considered a serious handicap to the overall logistics operation. As a final consideration, the integration of cargo and passenger transportation modes is considered unwise. The result would be a reduction in flexibility, safety, and efficiency. [Ref. 5: p. 478]

3. Elements of the Transportation System

Babb *et al.* [Ref. 27] provide a detailed description of possible elements of a lunar transportation system:

- Aerobraking Orbital Transfer Vehicle (AOTV)-- a 49 metric ton gross mass LO_2/LH_2 propulsion stage (42 metric tons of propellant)
- Expendable Lunar Lander (E-Lander)-- a LO_2/LH_2 landing stage with 13.6 metric tons of propellant that will land 17.5 metric tons
- OTV Manned Module (OMM)-- a 5.5 metric ton orbit-to-orbit reusable crew transport module with four personnel to be carried on the OTV
- Lunar Landing Module (LLMM)-- a 32.5 metric ton expendable module for temporary life support of four crew members during lunar landing and launching, attached to a 7.6 metric ton expendable launcher
- Reusable Lunar Lander/Launcher (R-LEM)-- a 5 metric ton LO_2/LH_2 single-stage vehicle utilizing lunar-produced propellant
- Reusable Lunar Landing Manned Module (R-LLMM)-- a 5 metric ton, six man, lunar-base crew compartment for the R-LEM maintained and stored at the lunar base
- Large OMM-- an enlarged, eight metric ton, reusable crew transport module for six personnel, carried on an OTV
- LH_2 Transfer Tank-- a one metric ton expendable container for carrying four metric tons of LH_2 to the lunar surface as fuel for the R-LEM
- Orbital Maneuvering Vehicle (OMV)-- a small, three or four metric ton, remotely operated propulsion stage to provide controlled close-in operations at the space station [Ref. 27: pp. 127-130]

These elements constitute one form of a transportation infrastructure and mission architecture described in Section A. The considerations in defining such an

infrastructure have already been discussed. The strategies of phased development and modular design have been incorporated in this infrastructure and consequently the lunar base. This particular configuration of elements is not necessarily the only composition possible. However, Babb *et al.* [Ref. 27] present this particular infrastructure based on launch requirements, cargo weight estimates, and a detailed manifest and mission schedule specified in their study.

Figure 6.5 [Ref. 27: p. 131] illustrates a possible manned flight scenario:

1. combined spacecraft elements depart space station
2. trans-lunar injection
3. first stage returns to space station
4. second stage, lander, and manned module inserted into lunar circular parking orbit
5. lander descends
6. ascent stage departs lunar surface
7. ascent module rendezvous with second stage
8. second stage returns to Earth with OMM, ascent module discards
9. aerobraking transfers OMM into elliptical Earth parking orbit (perigee below space station orbit)
10. circularization above space station orbit
11. rendezvous with space station

Unmanned flights are similar to the scenario depicted in Figure 6.5, except no cargo elements are left in orbit with the OTV, and none return from the lunar surface. The OTV returns to Earth empty. [Ref. 27: p. 131]

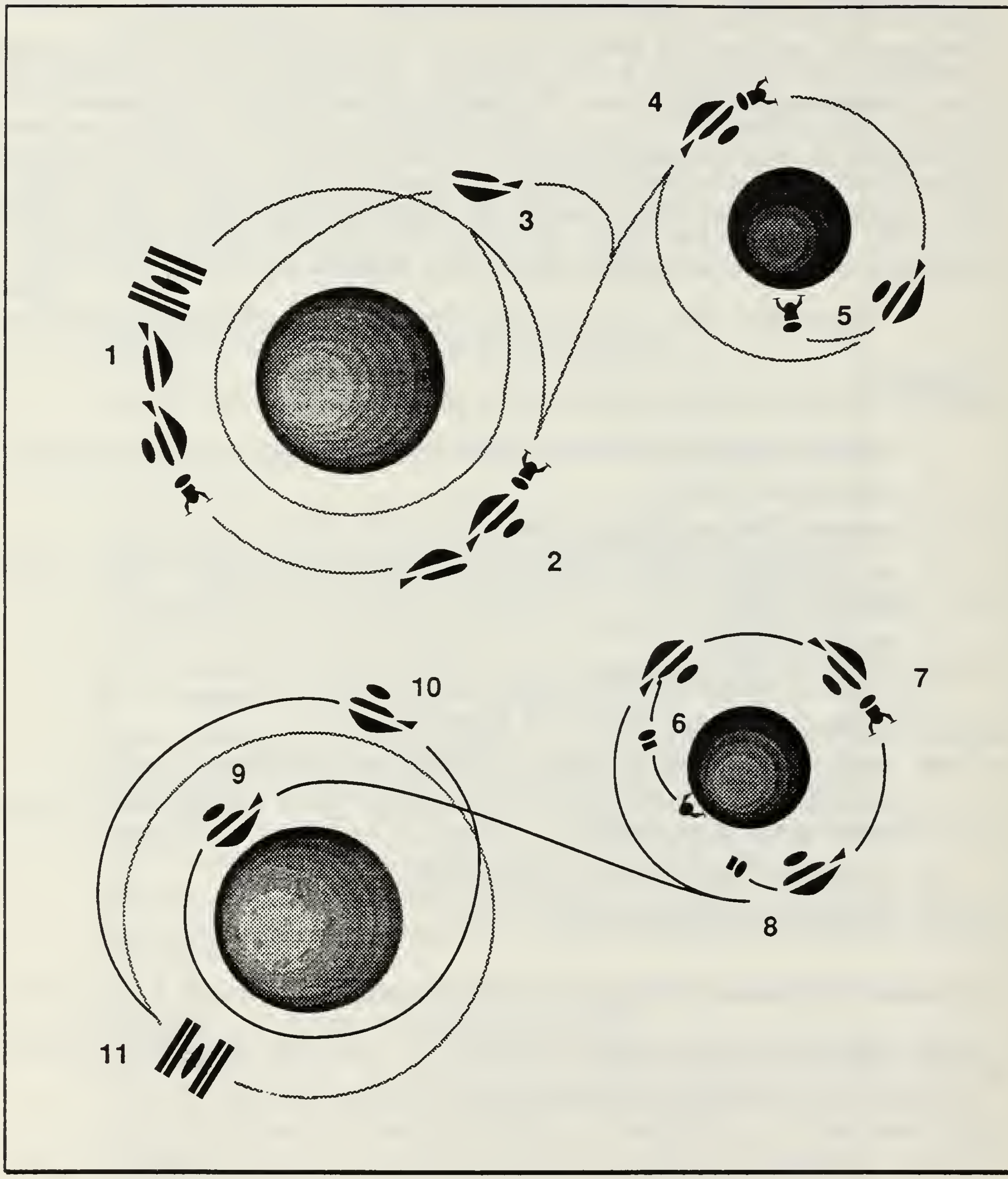


Figure 6.5 Manned Lunar Flight Scenario

D. TRANSPORTATION COSTS

Current transportation costs for space shuttle delivery of material to LEO are approximately $1000 per pound. Currently, a private company known as Pacific American Launcher Systems, is planning the development a reusable launch vehicle capable of transporting 20,000 pounds into LEO. Their goal is to reduce LEO orbit costs to $100 per pound [Ref. 28: p. 49].

The projected costs of transporting material to the lunar surface is approximately $10-15 thousand per pound. This figure is based on the development and eventual use of a shuttle-derived launch vehicle (SDLV). Even with the SDLV, two-thirds of lunar base cost will be transportation to the Moon. An initial objective to reduce the cost burden is the development of a high specific impulse, light-weight orbital transfer vehicle with aerobraking capability. Such a vehicle has already been described in the previous section as an integral part of the lunar support infrastructure. In addition, the capability to store propellants in the space environment for long durations is required. [Ref. 5: p. 16]

The key to an economical and affordable lunar base is the development of an effective and efficient space transportation system. The primary purpose of such a system is two-fold: the safe delivery of passengers to the Moon, and reliable cargo delivery. Much of the cost originates from the first leg of the lunar journey--Earth's surface to LEO. Figure 6.6 [Ref. 5: p. 480] illustrates the cost-effectiveness state-of-the-art represented by the space shuttle, improvements gained from a shuttle-derived launch vehicle (SDLV), and ultimately a heavy lift cargo vehicle (HLV). Transportation costs are strongly influenced by the cumulative payload to be lifted into orbit during the entire life-cycle costs of

these vehicles. Dividing the cumulative payload masses by the single flight capability of the respective vehicle results in the total number of flights required to achieve cost-effectiveness.

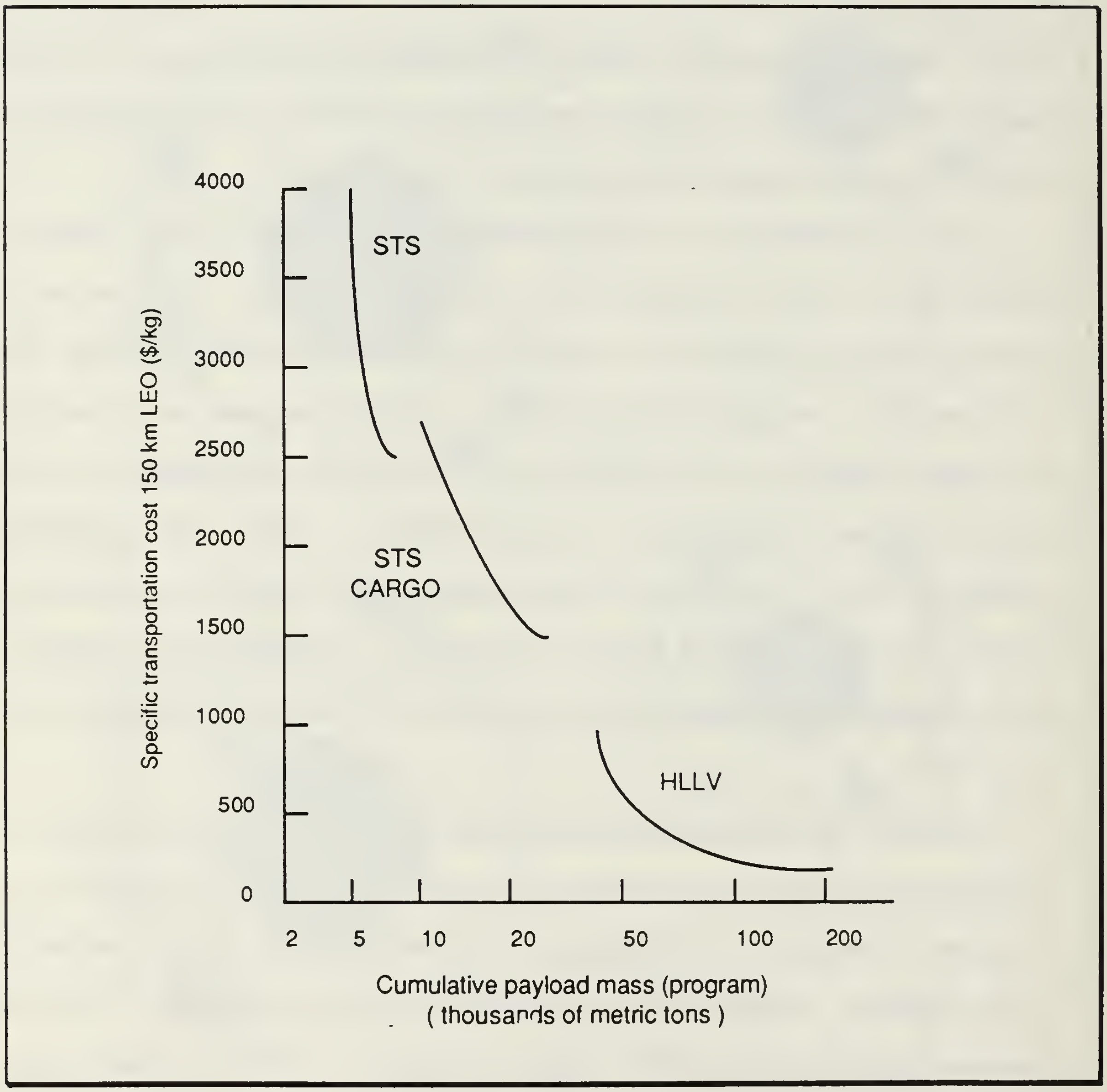


Figure 6.6 Cost-effectiveness of Launch Vehicles

E. LOGISTICS CONCLUSION

The attempt to establish a lunar base will be subjected to several "choke points" listed in Figure 6.7 [Ref. 2: p. 12]. The first bottleneck is Earth-to-orbit transportation. The need for larger payload launch capability has already been addressed. The next problem deals with transporting people. Longer mission stay times constitutes a small improvement and will ease the burden of transporting personnel. Another slowing obstacle is the transportation of cargo. At five kilograms per man-day, the cargo needed to sustain a ten person crew for 164 days is 8200 kg. Food growth and an effective closed ecological life-support system (CELSS) will decrease this number. The final choke point is the delivery of lunar base facilities. Initially, terrestrial hardware is required for growth. The only evident way to alleviate this problem is to utilize indigenous raw materials as soon as technologically feasible. Figure 6.7 identifies the problems related to each of choke points and possible solutions. [Ref. 2: pp. 11-12]

Woodcock's study on logistics support [Ref. 2] lists seven conclusions resulting from his research:

- all missions require fully reusable space transportation (with the noted exception of very modest missions)
- the lunar orbit rendezvous mode utilized by an aerobraked OTV complementing a lunar lander/launcher provides effective Earth-Moon transportation
- the number of lunar departures is such that the space station will serve as an adequate space station until the advanced stages of base evolution
- advanced lunar base technology required for growth necessitates advancements in CELSS, power, and lunar LOX
- a modest-sized lunar transportation system capable of delivering 10 people per trip or 17,000 kg (cargo-only) is adequate to support a base size of 1000 people

- large bases are affordable in a relative sense; logistics operations for a 1000-person base is less than twice as costly as the logistics required for a six-person base (assuming an orderly and plausible evolution of lunar base technology)
- the use of indigenous resources for production of capital facilities is required [Ref. 2: p. 12]

This chapter has dealt with transportation issues and has defined mission architecture and infrastructure considerations related to lunar base support. Flight mechanics were discussed in the context of orbital parameters, lunar librations, Lagrange points, and space station-lunar dynamics. Various mission modes were then compared and alternative trajectories were contrasted. A possible configuration of transportation elements was listed. Transportation costs were examined and logistics conclusions presented. The next chapter will list conclusions and recommendatio .s compiled from the information presented in the previous chapters.

Choke point	Problem	Fix
Earth-to-orbit transportation	Present fleet can't support even the smallest lunar base	Next-generation systems per NCOS & STAS
people transportation	Base size > 10 people exceeds number of departures/year supportable by space station	Longer stay time, e.g. duty tours with family
Cargo transportation	Longer stays drive lunar vehicles to large cargo capacity	CELSS (lunar food growth)
Lunar facilities	Hardware delivery for growth limits buildup rate	Indigenous lunar industry

Figure 6.7 Lunar Base Development "Choke Points"

VII. CONCLUSIONS AND RECOMMENDATIONS

This final chapter will summarize the findings of this thesis in two sections. The first section will review the material presented thus far. The second section will list conclusions and recommendations relating to the lunar base initiative.

A. SUMMARY

The material presented in the previous chapters delineated concepts and strategies required for a successful lunar base endeavor. In addition, a brief overview of critical technology was conducted in order to provide the necessary background knowledge prerequisite for evaluating the proposed strategies. Chapter I defined the scope and limitations of this thesis. Chapter II listed motivational considerations for establishing a lunar base. In addition, mission objectives were evaluated and cost considerations analyzed. Chapter III was the primary focus of this thesis and appraised strategy alternatives. Program requirements were defined and three alternative objectives were evaluated: science, industry, and self-sufficiency. Further, the concept of phased evolution in lunar base growth was analyzed. Alternative concepts of a remotely operated lunar base and a polar site location were evaluated. Finally in Chapter III, environmental considerations were appraised. Chapter IV compared various design layouts for a lunar base. Design concepts were assessed, radiation considerations were enumerated, and various proposed base structures contrasted. Power issues were examined in Chapter V. Various possible sources of lunar base power were surveyed and contrasted . Solar and nuclear forms of energy were compared, and the conceivable role of superconductivity was

presented. Chapter VI evaluated transportation factors related to a lunar base. Infrastructure support of a Moon base was delineated. In addition, flight mechanics were analyzed. Various mission modes were also compared. Finally, transportation costs were formulated and logistical conclusions were specified.

B. FINDINGS

The prospect of establishing a permanently manned lunar base is feasible. Much of the technology required for an initial lunar base endeavor has already been achieved. There is, however, a great deal of new technology required for the future growth of such a base. Fortunately, none of the required critical technologies present impossible tasks or require major breakthroughs in science. Crucial to the issue of feasibility is political support and public opinion. Without either of these two elements, budgetary support will not be possible. Funding considerations will impact the mission, since multi-year allocation of funds will be required. Although a lunar base endeavor will require substantial funding, the cost is not prohibitive, as discussed in Chapter II.

Currently, there are two major NASA efforts related to lunar base objectives. First, NASA has established the Office of Exploration. This branch of NASA is responsible for the examination of strategies for human exploration beyond Earth orbit. NASA now has a specific structure within the agency to study a manned lunar base and manned Mars mission concepts. Secondly, NASA has initiated a technology developmental program named "Pathfinder." The goal of project "Pathfinder" is to research and develop technology to be implemented in human exploration of the planets. "Pathfinder" is organized around four major thrusts:

- exploration
- operations
- humans-in-space
- transfer vehicles

Each thrust is directed at a group of critical technology components necessary to support critical mission areas. "Pathfinder" will support and closely interact with current NASA mission studies. [Ref. 10: p. 1]

In conclusion, no matter which option is chosen for the primary objective of the lunar base (science, industry, or permanent space exploration staging point) the advantages to be gained out-weigh the disadvantages to be overcomed. A permanent lunar base will make possible unique and valuable scientific data available in a wide range of research fields. Additionally, permanent access to lunar raw materials will decrease the logistical supply requirements from Earth. The presence of a lunar base will ultimately result in a more robust space infrastructure. However, a firm commitment to return to the Moon must be made as soon as possible. The importance of a long-term strategy has been discussed. Duke [Ref. 10] further elaborates on the importance of strategy in the following quote:

> The best way to insure program longevity appears to be to define a strategy that increases capability with time in such a manner that (a) return of new knowledge continually increases in quantity and quality; (b) technological capabilities visibly increases; and (c) operational costs are continually lowered. [Ref. 10: p. 5]

A well-planned lunar base mission incorporating strategies discussed in this thesis can fulfill the requirements above. NASA has conducted the first steps necessary by forming the Office of Exploration and initiating "Pathfinder." However,

development of the space station *Freedom* and the cargo variant of the space shuttle, Shuttle-C, must continue unhampered. Despite budget constraints and the ever-prominent concern for deficit reduction, funds must be provided for these current projects. The space station and Shuttle-C are primary components of the future lunar base support infrastructure, and will constitute the building blocks for subsequent elements of the infrastructure. In addition, unmanned remote sensing and geological survey missions to map and explore the Moon in detail must be conducted to evaluate possible base location sites. The activities mentioned above require no firm decision to initiate a lunar base program. However, when completed, the initial steps of an extensive and elaborate long-range space strategy will have been implemented. The prospect of establishing a lunar base becomes more likely if space activities continue to be funded with adequate priority.

APPENDIX A. POWER

This appendix provides supportive analyses for lunar base power plant design and power transmission. These analyses were provided by Prof. Don Wadsworth of the Naval Postgraduate School Department of Electrical and Computer Engineering. Figure A.1 is a conceptual design for a megawatt solar-electric power plant for a lunar base. It consists of a parabolic collector, a heat exchanger, a thermal-electric converter, and a heat radiator.

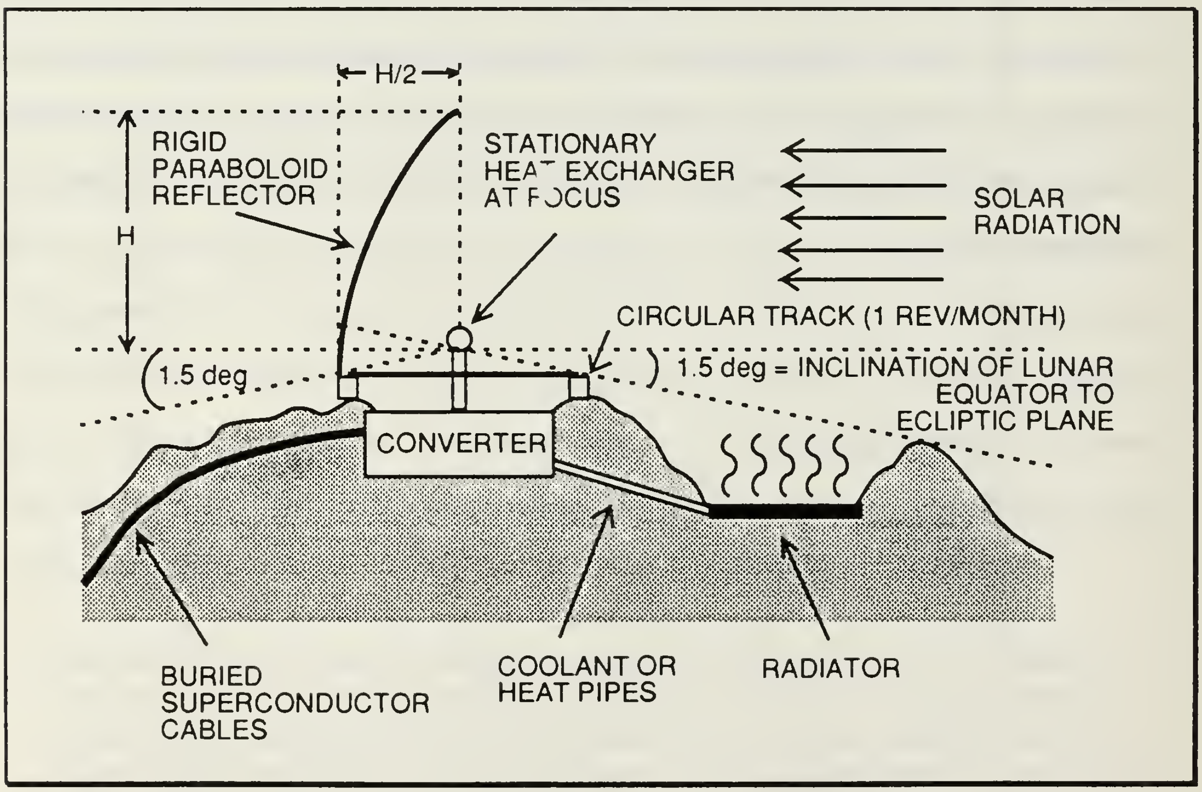


Figure A.1 Solar-Electric Power Plant at Lunar Pole

Two alternative implementations were considered for the converter:

- Free-piston linear alternator Stirling engine with gas bearings, liquid metal working fluid, and electromagnetic pump [Ref. 29: pp. 82-85, 205-208, 255-256]

- Brayton cycle engine with inert gas working fluid (~30 atmospheres pressure) and turbo-alternator-compressor [Ref. 29: pp. 85-88, 257, 239]

The following performance analysis applies to either alternative.

A. PERFORMANCE ANALYSIS

The electrical power output, P_e, is related to the collector aperture area, A, by $P_e = E_c \times E \times A \times 1350$. For the parabolic collector of Figure A.1, two point-design values are

P_e (MWe)	H (m)	A_r(m^2)
1	52	124
5	116	620

where A_r is the surface area of the heat pipe radiator. The A_r values were obtained by doubling the values given in Table 13.12 of Angelo and Burden's *Space Nuclear Power* [Ref. 29: p. 268] to account for hemispherical rather than isotropic radiation.

The above calculations were based on the following assumptions:

- Collector physical aperture, A ~ $\pi H^2/2$ m^2
- Collector efficiency, E_c ~ 0.7
- Thermal-electric conversion efficiency, E, = ~ 25%
- Solar constant ~ 1350 W/m^2

B. POWER PLANT MASS ESTIMATE

To minimize cost, a spherical reflector of the same aperture area could be used instead of the parabolic reflector. The heat exchanger would be a cylinder with its axis along the radius of the sphere. The cylinder would extend from R/2 to the spherical surface at radius R. The axis of the cylinder would be tilted from horizontal, over an annual cycle, to accommodate the ±1.5 degrees annual

variation in the angle-of-arrival of solar power. A disadvantage of the spherical reflector design is that a high-pressure rotary coupling is required for the working fluid at the nonstationary (360°/month) heat exchanger.

The converter could be designed to be compatible with an auxiliary nuclear reactor, providing back-up or peak load power. The same turbine and working fluid could serve both heat source options.

The total mass of the solar power plant and consequently the mass which must be lifted to LEO can be estimated as follows. The starting point is the mass estimate, given in the left-hand column below, for a 1 MWe space nuclear reactor plant using a 25% efficiency Stirling cycle converter, a heat radiator, and shield [Ref. 29: p. 268]. The right-hand column is the solar power system estimate.

Nuclear Power System		Solar Power System	
nuclear reactor	860	solar reactor	1000
primary loop	290	primary loop	290
shield	880	shield	0
converter	875	converter	875
radiator	621	radiator	1242
structure (10% of total)	394	structure (10%)	378
Total:	3920 kg	Total:	3785 kg

The mass estimate for the solar reactor is a nominal value. The solar system radiator area is double the nuclear system value since the former is located on the lunar surface.

The mass of the solar collector can be estimated using the specific mass, m_s, for graphite-epoxy antenna structures used on communications satellites (e.g., Intelsat VI). Typically, $m_s = 6 \ \frac{kg}{m^2}$ provides a rigid, low-thermal distortion antenna with a metalized reflecting surface. Such an antenna must be designed for pre-flight communications testing on the Earth's surface; consequently, it

can easily accommodate stresses due to the lunar surface gravity. The surface area of a spherical reflector ($\frac{1}{4}$ of a sphere) of radius H = 52 m^2 is πH^2 ~8,500 m^2. The actual collector area could be about ten percent less, since a full quarter-sphere would be inefficient. A conservative value, then, for the collector mass is 0.9 x 8500 x 6 = 45,900 kg or about 46 tonnes. An additional five to ten tonnes is required for the 327 m of track rail, track support structure, and drive mechanism. The total mass required to be lifted to LEO is, conservatively, about 5 x 60 = 300 tonnes, where the factor of five is explained in Chapter V, page 87.

C. POLAR SITE ELEVATION

The ± 1.5 degrees annual variation in solar energy angle-of-arrival requires a site elevation, h, above the mean lunar surface to avoid shadowing. For a mean lunar radius of 1738 km,

$$h = \frac{\left(\frac{1.5}{57.3}\right)^2 (1738)}{2} = 0.6 \text{ km.}$$

D. POWER TRANSMISSION

Power transmission to the lunar base could be via conventional cables, either buried or overhead. Lossless superconducting cables are a possibility near the poles if they can be kept at a temperature of about 70 K or less. They may not be feasible at lower latitudes where Apollo measurements [Ref. 30: p.432-433] found subsurface temperatures of 250 K with a 1.75 K/m increase with depth, presumably caused by radioactivity (see also Ref. 21: p. 360).

If the heat of flow of $I_o = 0.03\ W/m^2$ measured at the Apollo sites [Ref. 30: p. 432] applies to polar regions (where there is no heating by solar radiation), then the polar surface temperature T would be given by the Stefan-Boltzman law for a black body radiating into deep space:

$$T = \left(\frac{I_o}{ke}\right)^{1/4} = \left(\frac{0.03}{(5.5699 \times 10^8)(0.9)}\right)^{1/4} = 28\ K$$

where $k = 5.669 \times 10^8\ W/m^2 \bullet K^4$ is the Stefan-Boltzman constant and $e = 0.9$ is the assumed emissivity of the lunar surface.

Evidently, surface or buried power cables in the permanently shadowed polar regions would be naturally maintained at superconducting temperatures.

APPENDIX B. ARTIFICIAL GRAVITY

The following concepts on lunar base artificial gravity are based on analyses by Prof. Don Wadsworth of the Naval Postgraduate School Department of Electrical and Computer Engineering.

The lunar environment's gravitational acceleration is only 1/6 that on the Earth's surface: $g_m = 0.16\ g_e$ where $g_e = 9.8$ m/s^2. This may not be sufficient to prevent long-term physical deterioration of the lunar base crew. One solution may be to provide "artificial gravity" equivalent to "1-gee" or 9.8 m/s^2 during crew sleep periods (this has yet to be demonstrated as adequate). Two methods are described in this section.

Centrifugal acceleration due to rotation about a fixed center can supply the artificial gravity. However, tests have shown that the non-uniform acceleration field can cause crew disorientation, unless the radius of rotation is sufficiently large [Ref. 31: p. 109]. This radius is about 1.5 km for a 1-gee field. For sleeping quarters, the tolerance is much higher, so that a smaller radius is acceptable, perhaps as small as the 100 m assumed in the following analyses.

A. CAROUSEL DESIGN

One possibility for artificial gravity is to attach a pair of sleeping cars or gondolas to a rotating boom, as in a centrifuge or carousel (see Figure B.1). As the rotation rate increases, the gondolas pivot so the net acceleration is always normal to the floor. The gondolas would, of course, contain lavatories but no work quarters. The gondola access (via ladder or elevator) is in the floor which simplifies mating to the surface hatch. In contrast, side access hatches would

have to allow clearance for gondola swing about the pivot. The design easily accommodates additional gondola pairs. For a radius R=100 m, the gondola speed would be $v=\sqrt{9.8R}$ = 31 m/s (70 mph) and the rotation period $T=2\pi R/v$ = 20 seconds. To minimize materials cost, the minimum acceptable radius would be chosen.

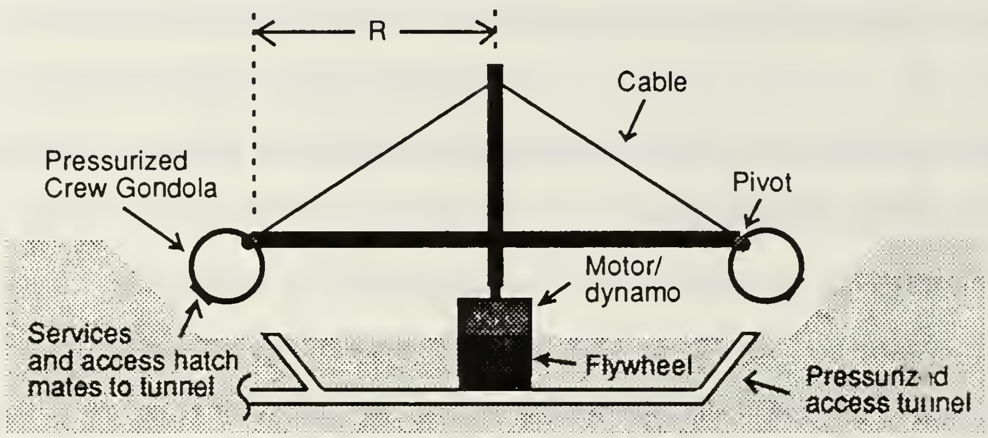


Figure B.1 Artificial Gravity Carousel

Energy costs could be minimized and braking simplified by means of a motor/dynamo set to transfer energy from the carousel to a flywheel. Two carousels could also do the job. They could be stacked vertically or side-by-side.

Disadvantages of the design, due to the gondola exposure, are the expense of temperature control, the expense of radiation shielding, and the vulnerability to meteorite (or hostile attack) damage. A location in a crater near the poles would minimize the solar proton event flux (a quantitative analysis is needed). Also, such a location would avoid the monthly temperature cycling from solar heating.

Of course, at additional cost, the carousel could be located under a protective roof with perhaps two meters of regolith overburden for shielding. The roof trusses would have to span at least 100 meters.

A limitation of the simple carousel design is the need to stop the entire system for access by different shifts, implying rigid scheduling. A more complex design could provide access without stopping by means of a pressurized tube attached to the boom. Personnel would enter at the hub and be transported on a moving seat or elevator to the gondola while it is rotating. If the carousel was continually rotating, the gondola could be rigidly attached, at the preferred angle, to the boom and access tube. Otherwise a flexible or disconnectable tube coupling would be required.

B. ROLLERCOASTER DESIGN

The "rollercoaster" artificial gravity design is shown in Figure B.2. The pressurized sleeping cars free-fall down the inclined track from the "station" until they reach the desired speed for transfer onto a circular track of radius R. The cars would use momentum to coast uphill to the station. For R=100, the free-fall drop, h, is equal to 3R=300 m. The slope of the incline is an open design parameter (30° was chosen for the illustration in Figure B.2). The track could be exposed or located in an evacuated tunnel or covered trench. The latter case solves the monthly heating cycle, radiation and meteorite exposure problems, at added cost. A polar location might avoid the need for underground tracks.

Possible disadvantages, compared to the carousel design, are the temporary convenience of the free-fall (31-second duration for 100 m track radius), the fairly rapid transition from 0.16 g_e to 1 g_e (5 to 10 seconds for a 100 m radius),

the greater hazard due to debris on the track, the possibility of track switch failure (jamming by debris), and increased energy loss due to friction. Electromagnetic levitation could minimize the latter. An emergency stop on the circular track would require some mechanical means of retaining the car on the track in its sideways position. A 1 g_e emergency stop would take 300 m, or nearly a half revolution.

An advantage of the roller coaster design, compared to the simple carousel design, is the flexible scheduling without shutting down the system. The sleeping cars would always travel on the circular track while detachable shuttle cars would permit transfer to the station at any time. The shuttle car, attached to the end of a sleeping car train, would detach and drop behind, allowing time to switch onto the exit track. In addition to momentum, a small propulsion motor would be required to overcome losses.

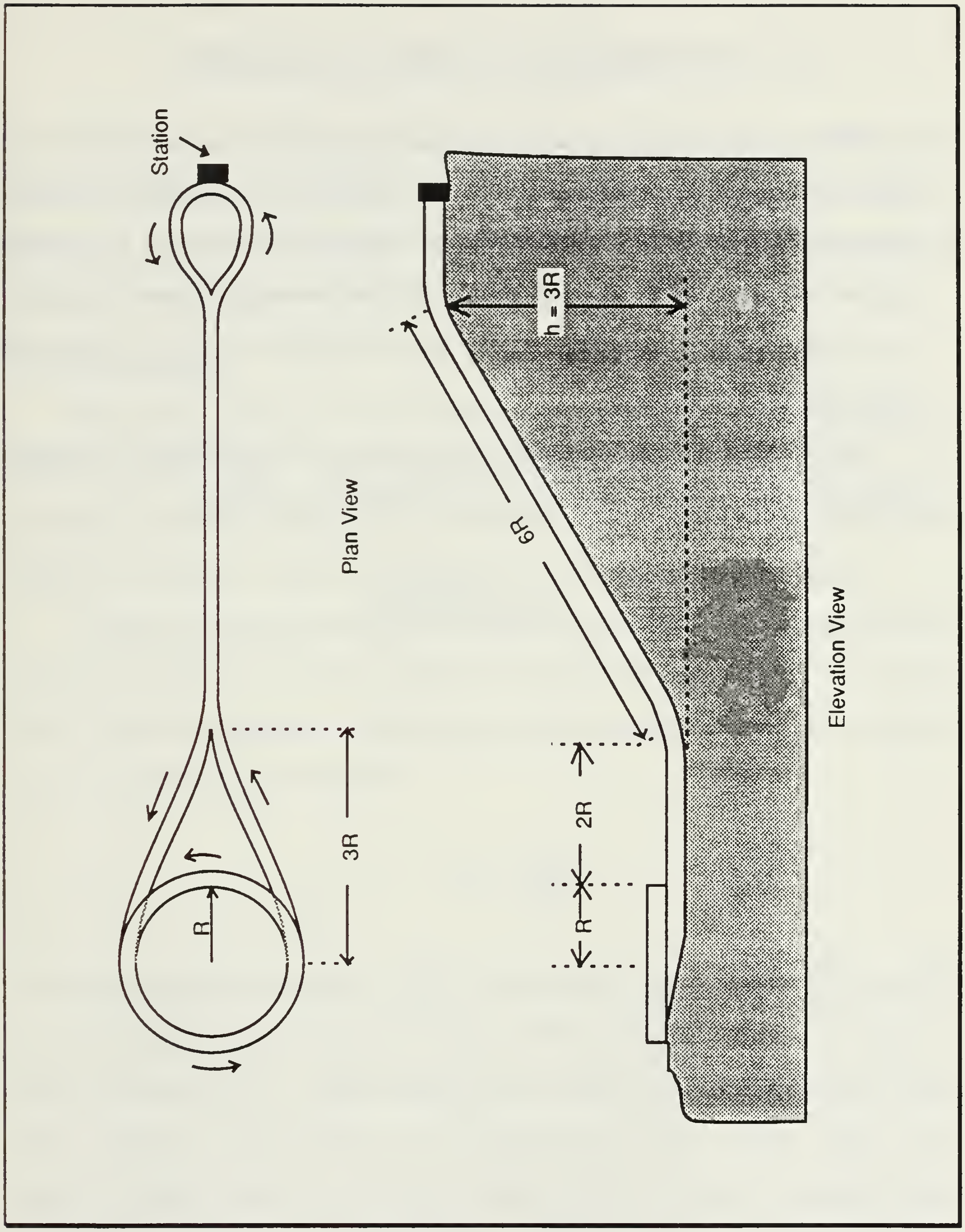


Figure B.2 Artificial Gravity Rollercoaster

APPENDIX C. COMMUNICATIONS

Radio relay and fiber-optic cables are possibilities for wideband, lunar surface communication routes. Because the radius of curvature of the lunar surface is about one-fourth that of Earth, the mean distance between line-of-sight repeater towers would be one-half that on Earth (assuming similar topography). Thus a lunar repeater route may require twice as many repeaters as a terrestrial route of the same distance.

The line-of-site distance between two towers, each at height h, above a spherical surface of radius R is given by the following equation:

$$d \sim 2^{3/2}(Rh)^{1/2}$$

APPENDIX D. POLAR CONSIDERATIONS

This appendix provides permafrost layer calculations based on analyses by Prof. Don Wadsworth of the Naval Postgraduate School Department of Electrical and Computer Engineering. In addition, environmental considerations of a polar site location are presented.

A. POLAR ICE

Since water freezes at 273 K, there might be a lunar permafrost layer at approximately $\frac{(273\text{-}28)}{1.75} = 140$ m depth in the polar shadow region, assuming the measured 1.75 K/m gradient holds. Obviously, this gradient must fall off with depth, or the Moon would be molten below one or two kilometers depth.

A crude bound for the depth of the permafrost layer can be obtained from a simple calculation, assuming a uniform semi-infinite slab model for the Moon which ignores radioactive heat sources above the permafrost. The uniform, steady-state heat flow relation is:

$$I_0 = -k\left(\frac{dT}{dx}\right)$$

where I_0 is the heat flow rate in $\frac{W}{m^2}$, k is the thermal conductivity in $\frac{W}{m \bullet K}$, and $\frac{dT}{dx}$ is the thermal gradient in K/m. For $I_0 = 0.03$ and $\frac{dT}{dx} = 1.75$ at the surface, it follows that k = 0.017 which is similar to the conductivity of diatomaceous earth. This figure is remarkably low compared to Earth rocks which have conductivities in the 0.5 to 2.0 range. Since the conductivity at depth should increase, the temperature gradient should fall-off accordingly. If the mean value for k = 1.0, then, assuming $I_0 = 0.03$ at the bottom of the permafrost layer, the

mean gradient would be 0.03 K/m. The present lower boundary of the permafrost layer would be at $\frac{273\text{-}28}{0.03} \sim 8000$ m depth.

If the lunar temperature profile has remained constant, the permafrost layer might be only a few meters or tens of meters thick, since upward migrating water or water vapor would freeze out. On the other hand, if the Moon has been steadily cooling during its history, the fossil permafrost could be distributed from near the surface to the present melt zone. The overlying regolith would inhibit sublimation. The permafrost water, if it exist, might be obtained by pumping from electrically-heated wells.

Supposing an abundance of water could be collected, it is reasonable to assume the base might have a recreational swimming pool. By Archimedes principle, a swimmer would float a the same level as on Earth. However, for the same height dive, the time of free-fall would be increased by a factor of $\sqrt{6} = 2.4$, permitting impressive acrobatics. The water impact velocity, for the same height diving board, would be reduced by the same 2.4 factor.

B. CREW ENVIRONMENT

Surface structures near the pole would require heating for human habitation and also electronics. If the 1.75 K/m temperature gradient applies at the poles, then a comfortable temperature of 295 K would occur naturally in quarters at a depth of 152 m. Of course crew quarters need not be at 150 m depth to be heated passively. Heat pipes could transmit the heat from 150 m to surface structures. Buried structures at the polar power plant site could even be provided with full-time, natural lighting by means of passive surface reflectors or lenses and vertical shafts or fiber optic cable bundles (see also Ref. 14: p. 81).

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